dtec.bw
Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr

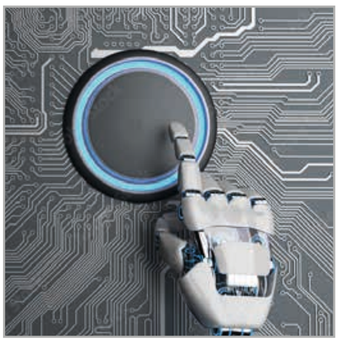
Detlef Schulz, Alexander Fay, Wenzel Matiaske, Manuel Schulz (Hrsg.)

dtec.bw-Beiträge

der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Forschungsaktivitäten im Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr dtec.bw

Band 1 · 2022



EnDig
KIIPS
KoDiA
OPAL

Druckversion: ISBN 978-3-86818-316-0
Digitale Version: ISBN 978-3-86818-315-3

DOI: https://doi.org/10.24405/14522

Der Sammelband wird veröffentlicht durch:
dtec.bw – Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Herausgeber:
Detlef Schulz, Alexander Fay, Wenzel Matiaske, Manuel Schulz

Adresse:
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg, Holstenhofweg 85, 22043 Hamburg

Telefonnummer: +49 40 / 6541 - 1
E-Mail: dtecbw@hsu-hh.de

Gestaltung Einband:
Michael Bölke, Medienzentrum, Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Bildnachweis Titelseite:
Bildwerk (Serveromputer)/HSU, stock.adobe.com/Button blau, stock.adobe.com/IT-Spezialistin, E-Auto/HSU

dtec.bw-Beiträge der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Forschungsaktivitäten im Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr dtec.bw Band 1 · 2022

mit Beiträgen der Dachprojekte:
Energie und Digitalisierung (EnDig),
Künstliche Intelligenz und Intelligente Physische Systeme (KIIPS),
Kompetenzen für die digitale Arbeitswelt (KoDiA),
Organisation – Personal – Arbeit – Leadership (OPAL)
von der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Hamburg, Dezember 2022

Herausgeber:

Prof. Dr.-Ing. habil. Detlef Schulz
Prof. Dr.-Ing. Alexander Fay
Prof. Dr. phil. habil. Manuel Schulz
Prof. Dr. Wenzel Matiaske

Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Holstenhofweg 85, 22043 Hamburg
Tel.: +49 40 / 6541 - 1
E-Mail: dtecbw@hsu-hh.de
Internet: https://dtecbw.de

Redaktionelle Überarbeitung:

Detlef Schulz
Henrik Wienken
Oliver Schmalholz

dtec.bw
Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr

Inhaltsverzeichnis

Vorworte

Kapitel I Energie und Digitalisierung (EnDig)

Kapitel II Künstliche Intelligenz und Intelligente Physische Systeme (KIIPS)

Kapitel III Kompetenzen für die digitale Arbeitswelt (KoDiA)

Kapitel IV Organisation – Personal – Arbeit – Leadership (OPAL)

Vorworte zum Sammelband „dtec.bw-Beiträge der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg“

mit Beiträgen von

Vorwort der Herausgeber:

Prof. Dr.-Ing. habil. Detlef Schulz
Prof. Dr.-Ing. Alexander Fay
Prof. Dr. phil. habil. Manuel Schulz
Prof. Dr. Wenzel Matiaske

Vorwort des Präsidenten
der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Prof. Dr. Klaus Bertram Beckmann

Vizepräsidentin für Forschung
der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Prof. Dr. jur. Margarete Schuler-Harms

Vorwort der Herausgeber zum dtec.bw-Sammelband

Im vorliegenden Sammelband finden Sie wissenschaftliche Beiträge aus den Forschungsprojekten im „Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr“ (dtec.bw). Die thematische Strukturierung der Forschungsgebiete erfolgt in vier Dachprojekten:

- Energie und Digitalisierung (EnDig)
- Künstliche Intelligenz und Intelligente Physische Systeme (KIIPS)
- Kompetenzen für die digitale Arbeitswelt (KoDiA)
- Organisation – Personal – Arbeit – Leadership (OPAL)

Innerhalb der Dachprojekte gibt es jeweils eine Vielzahl von Einzelprojekten zu unterschiedlichen Themengebieten. Im Sommer 2022 entstand deshalb in Diskussionen zwischen den Dachprojektleitern die Idee, in einem Sammelband die aktuellen Zwischenergebnisse der Projekte zusammenzufassen und damit einerseits mehr Transparenz für alle Beteiligten zu schaffen und andererseits die Öffentlichkeit detaillierter über die laufenden Projekte zu informieren.

So entstanden in einem relativ kurzen Zeitraum von August bis Oktober 2022 die hier vorgestellten Zusammenfassungen der bisherigen Projektergebnisse bzw. Ausblicke auf zukünftige Aktivitäten. Die Themenauswahl wurde den Autoren freigestellt, um den unterschiedlichen fachlichen und organisatorischen Randbedingungen sowie der spezifischen Fächerkultur Rechnung zu tragen.

Wir bedanken uns herzlich bei allen beteiligten Autoren der Einzelprojekte für den Zuspruch zu diesem Sammelband und das große Engagement aller Beteiligten zur Einhaltung des eng gesteckten Zeitplans. Vielen Dank dafür, dass Sie zum Gelingen dieses ersten dtec.bw-Sammelbands beigetragen haben!

Unser besonderer Dank gilt Herrn Henrik Wienken und Herrn Oliver Schmalholz für die organisatorische Unterstützung durch die Bereitstellung der Vorlagen, die redaktionelle Bearbeitung und die vielen Hilfsangebote an die Autoren.

Bei Herrn Bölke vom Grafikstudio bedanken wir uns für die kreative Unterstützung bei der Gestaltung des Einbands.

Den Mitarbeitern der Universitätsbibliothek danken wir uns für die freundliche Unterstützung bei der Veröffentlichung.

Dieser Band wird neben der Veröffentlichung als Druckversion auch online über die Bibliothek der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg zur Verfügung gestellt:

https://ub.hsu-hh.de/

Wir wünschen Ihnen viel Freude beim Lesen und freuen uns auf die weitere intensive Zusammenarbeit mit Ihnen!

Hamburg, im November 2022

Detlef Schulz, Alexander Fay, Wenzel Matiaske, Manuel Schulz

Vorwort des Präsidenten der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Das Programm dtec.bw ist etwas ganz Besonderes aus einer anderen Welt. In der normalen Welt streiten sich die größten und bekanntesten Universitäten Deutschlands um einen der begehrten Plätze in der Exzellenzinitiative, sei es als Exzellenzuniversität per se, sei es durch Einbringen eines Exzellenzclusters. Welche Mittel bei Erfolg konkret über welchen Zeitraum fließen, streut erheblich.

Jedenfalls geht es dort nicht um 250 Mio. € über vier Jahre. Dies ist aber gerade der Förderbetrag, der für jede der beiden Universitäten der Bundeswehr (die zusammen etwas mehr als 5000 Studierende haben) aufgerufen wurde. Notabene nicht mit dem Zweck der Wissenschaftsförderung, sondern als Maßnahme im Rahmen der Konjunkturpolitik zur Überwindung der Corona-Krise. Mit einem thematischen Schwerpunkt bei der Stärkung der digitalen Souveränität Deutschlands. Angekündigt im Juni 2020 mit einer finalen Entscheidung im August desselben Jahres.

Was für eine Chance für die Universitäten der Bundeswehr, und was für eine organisatorische Herausforderung! Wir haben in den beiden Häusern unmittelbar agiert. Bei uns in Hamburg ging es vor allem um zweierlei: erstes um die Etablierung eines wettbewerblichen Vergabefahrens unter erheblichem Zeitdruck und zweitens um eine Ausrichtung des Vorhabens an vier Dachprojekten, welche die Stärken unseres Hauses widerspiegeln. Dabei galt es auch, die Interdisziplinarität unserer Fakultäten als Alleinstellungsmerkmal zu stärken.

Uns allen ist klar: Geld und Ausstattung allein begründen keine "Exzellenz in der Forschung", wie immer man diese definieren und messen mag. Aber sie erleichtern es, ein Umfeld zu schaffen, in dem sich gute Forschung entwickeln kann, und sie ermöglichen teilweise erst die zur Erreichung von Größenvorteilen erforderlichen Kooperationen.

Der vorliegende Band versammelt Berichte zu einigen dtec-Projekten der HSU/UniBw H und trägt so dazu bei, den aktuellen Stand bei dtec.bw zu dokumentieren, zumindest soweit es die Hamburger Beiträge betrifft. Dabei werden Ansätze, Methoden und erste Ergebnisse der Digitalisierungsforschung des dtec.bw über dessen ganze Breite aufgezeigt. Weil Digitalisierung ein Querschnittsthema in Forschung und Wissenstransfer darstellt, erscheint das als angemessen.

Dem Band wünsche ich diejenige Aufnahme, die ihm angesichts der Bedeutung des Themas und unserer Verantwortung für das ungewöhnliche Großprojekt gebührt: eine intensive. Ich bedanke mich bei dem Kollegen Prof. Dr. Detlef Schulz, den anderen drei Dachprojektleitungen und dem Redaktionsteam dafür, dass er zustande gekommen ist.

Hamburg, im Dezember 2022

Prof. Dr. Klaus Bertram Beckmann

Präsident der Helmut-Schmidt-Universität/Universität der Bundeswehr Hamburg

Vorwort der Vizepräsidentin für Forschung der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Das von den beiden Universitäten der Bundeswehr in München und Hamburg getragene Forschungsprogramm dtec.bw ging Ende 2020 an den Start. Als Teil des Konjunkturförderprogramms der Bundesregierung wurde es vom Bundesministerium der Verteidigung zunächst auf vier Jahre angelegt. Seit einiger Zeit ist es außerdem Bestandteil des Deutschen Aufbau- und Resilienzplans.

In 68 Projekten ganz unterschiedlichen Umfangs wird seitdem zu Digitalisierung und Technologieentwicklung sowie zu den gesellschaftlichen Wirkungen des digitalen Wandels an beiden Universitäten geforscht und dabei mit Personen und Einrichtungen aus Wissenschaft, Wirtschaft, Verwaltung und Bundeswehr sowie der Gesellschaft kooperiert. Erstmals arbeiten im dtec.bw auch die beiden Universitäten eng zusammen. Sie bilden nicht nur ein gemeinsames Leitungsteam mit Gesamtleitung und Geschäftsstelle in München, auch in 16 der 68 Projekte kooperieren Forschende aus beiden Universitäten. Gleichwohl – und in der Programmatik angelegt – trägt das dtec.bw an jeder Universität eine ihr spezifische Signatur.

Das dtec.bw wurde als Forschungsprogramm zu Digitalisierung und Technologieentwicklung thematisch weit gefasst. So bedeutsam diese Themen auch für Bereiche der Verteidigung und Sicherheit auch sind, fokussiert das dtec.bw doch hierauf nicht allein; und ungeachtet eines deutlichen Anwendungsbezugs ermöglicht und fördert es auch Forschung zu Grundlagen. Das dtec.bw ist weder eine Einrichtung der Ressortforschung, noch wurde eine eigenständige, von den Universitäten unabhängige Organisationsstruktur geschaffen. In bekannte Vorbilder fügte und fügt sich das dtec.bw nicht ein. Auch deshalb war und ist es für die Universitäten herausforderungsvoll.

Der vorliegende Sammelband präsentiert die Signatur des dtec.bw an der Helmut-Schmidt-Universität. Sichtbar wird sie u.a. in der Breite der Forschungsthemen und in der Zuordnung der Beiträge zu den vier „Dachprojekten", d.h. zu den hier im dtec.bw gebildeten Forschungsschwerpunkten.

Den Herausgebern danke ich für die Idee zu diesem Sammelband und seine Organisation entlang der Dachprojekte. Mein herzlicher Dank gilt auch all jenen, die hier in vielen Beiträgen über ihre Forschung berichten. Ganz besonders danke ich meinem Kollegen, Univ.-Prof. Dr.-Ing Detlef Schulz, und seinem Team, die durch eine straffe Konzeption und Führung sowie ein hervorragendes Lektorat dieses Werk ermöglicht haben.

Hamburg, im Dezember 2022

Prof. Dr. jur. Margarete Schuler-Harms

Vizepräsidentin für Forschung der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Kapitel I

Energie und Digitalisierung (EnDig)

mit Beiträgen von

Airbus Defence and Space GmbH

Bundesanstalt für Materialforschung und –prüfung

Eurotechnica GmbH

GTT-Technologies

H.Loitz Robotik

Helmholtz-Zentrum Hereon

Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Impact Innovations GmbH

Karlsruhe Institute of Technology

Kühne Logistigs University

Lufthansa Technik AG

Megware Computer Vertrieb & Service GmbH

Physikalisch-Technische Bundesanstalt Berlin

Technische Universität Berlin

Technische Universität Hamburg

Technische Universität München

Universität der Bundeswehr München

Universität Stuttgart

Vorwort zum dtec.bw-Dachprojekt „Energie und Digitalisierung (EnDig)“

Eine zuverlässige und kostengünstige Energieversorgung ermöglicht gesellschaftliche Entwicklung und sichert Wohlstand und Komfort. Sie muss klimaneutral und damit nachhaltig gestaltet werden, um unseren Lebensraum auch für nachfolgende Generationen zu sichern. Die dafür notwendigen technischen Weiterentwicklungen erfordern in vielen Bereichen die Digitalisierung von Prozessen. Aufgrund der hohen strategischen Bedeutung der Energieversorgung handelt es sich hierbei meist um sog. kritische Infrastrukturen, die eine besondere Herangehensweise bei der Digitalisierung erfordern. Diese und viele andere Randbedingungen werden im Dachprojekt „Energie und Digitalisierung“ berücksichtigt.

Wissenschaftler können dazu beitragen, dass innovative Ideen, daraus abgeleitete Zielstellungen und neue Technologien zur Weiterentwicklung unserer Gesellschaft gefunden, erprobt und schließlich in großer Breite angewendet werden. Die Zielstellungen in unserem Dachprojekt sind dabei vielfältig, sie sollen verschiedene, gesellschaftlich relevante Themen befördern:

Das Dachprojekt "Energie und Digitalisierung" soll in den Zielbereichen Wasserstoff, Smart Grid, Klimaschutz, Erneuerbare Energien, klimaneutrale Luftfahrt, Hafenlogistik, maritime Technologien und digitale Produktion konjunkturfördernd wirken. Insgesamt soll die Wettbewerbsfähigkeit der deutschen Industrie durch Projekte zur Digitalisierung im Energie- und Produktionssektor gestärkt werden. Hierbei spielen insbesondere die in Deutschland entstehende Wasserstoffwirtschaft mit ihren Möglichkeiten zur Sektorenkopplung und Energiespeicherung, die Umstellung auf „grüne“ Energieerzeugung und die Elektromobilität eine große Rolle. Neue Technologien können nur dann schnell entworfen, entwickelt, zu marktfähigen Preisen produziert und flexibel genutzt werden, wenn alle Prozesse durchgehend digitalisiert werden. Forschungs-, Kooperations- und Demonstrationsprojekte mit Industriepartnern sollen die Innovationskraft Deutschlands stärken und konjunkturelle Anreize setzen.

Alle vorliegenden Beiträge wurden im Zeitraum August bis Oktober 2022 erstellt. Es ist sehr erfreulich, dass bereits nach 20 Monaten Laufzeit erste Zwischenergebnisse aus allen Einzelprojekten in Form von neuen Forschungsansätzen, wissenschaftlichen Methodiken, Simulationen, Themenstudien und Umsetzungskonzepten für Demonstratoren präsentiert werden können.

Besonders freue ich mich darüber, dass viele dieser Beiträge unter Beteiligung unserer nationalen und internationalen Kooperationspartner aus der Wissenschaft und Industrie entstanden sind.

Ich möchte mich bei allen beteiligten Autoren des Dachprojekts "Energie und Digitalisierung" dafür bedanken, dass Sie bereit waren, trotz der vielen anderen Aufgaben in ihren laufenden Projekten mit viel Engagement zum Gelingen dieses ersten dtec.bw-Sammelbands beizutragen.

Dieser Band wird neben der Veröffentlichung als Druckversion auch online über die Bibliothek der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg zur Verfügung gestellt:

https://ub.hsu-hh.de/

Ich wünsche Ihnen viel Freude beim Lesen und freue mich auf die kommenden Diskussionen sowie Ihre Anregungen, gern auch für mögliche Themen zu den Beiträgen der kommenden Jahre, denn die Zielstellungen in unserem Dachprojekt "Energie und Digitalisierung" sind sehr vielfältig und können nur gemeinsam erreicht werden.

Hamburg, im November 2022

Detlef Schulz

Dachprojektleiter "Energie und Digitalisierung"

Analyse und Charakterisierung aktueller Siliziumkarbid-Bauelemente für ein digitales Lebenszyklus-Monitoring robuster Leistungselektronik in kritischer Infrastruktur

Sönke Brandt
Professur für Leistungselektronik
Helmut-Schmidt-Universität,
Universität der Bundeswehr Hamburg
Hamburg, Deutschland
soenke.brandt@hsu-hh.de

Martin Rasch
Professur für Leistungselektronik
Helmut-Schmidt-Universität,
Universität der Bundeswehr Hamburg
Hamburg, Deutschland

Klaus Hoffmann
Professur für Leistungselektronik
Helmut-Schmidt-Universität,
Universität der Bundeswehr Hamburg
Hamburg, Deutschland

Simon Podendorf
Professur Grundlagen der Elektrotechnik
Helmut-Schmidt-Universität,
Universität der Bundeswehr Hamburg
Hamburg, Deutschland

Ahmet Buran
Professur Grundlagen der Elektrotechnik
Helmut-Schmidt-Universität,
Universität der Bundeswehr Hamburg
Hamburg, Deutschland

Stefan Dickmann
Professur Grundlagen der Elektrotechnik
Helmut-Schmidt-Universität,
Universität der Bundeswehr Hamburg
Hamburg, Deutschland

Eden Tulu
Professur für Theoretische Elektrotechnik
und Numerische Feldberechnung
Helmut-Schmidt-Universität,
Universität der Bundeswehr Hamburg
Hamburg, Deutschland

Marcus Stiemer
Professur für Theoretische Elektrotechnik
und Numerische Feldberechnung
Helmut-Schmidt-Universität,
Universität der Bundeswehr Hamburg
Hamburg, Deutschland

***Kurzfassung*—Leistungselektronik in kritischer Infrastruktur muss in besonderem Maße betriebssicher sein. Der Einsatz moderner unipolarer Siliziumkarbid-Leistungshalbleiter ermöglicht die Realisierung hocheffizienter Stromrichtereinheiten mit hoher Leistungsdichte. Für die Erhöhung ihrer Resilienz ist die Kenntnis der Ausfall- und Fehlermechanismen sowie die exakte Beschreibung des Schalt- und Leitverhaltens der neuen unipolaren Wide-Bandgap-Leistungshalbleiter unverzichtbar. In diesem Zusammenhang wurde in dem Forschungsprojekt DiMoLEK eine hochkomplexe Testschaltung für die Doppelpuls-Analyse entwickelt. Diese zeichnet sich durch eine adaptive Ansteuerungstechnologie mit einem extrem niederinduktiven Kommutierungskreis aus. Der Einsatz neuester Messtechnik ermöglicht die Erfassung und Auswertung von Messsignalen bis in den Gigahertz-Bereich, wodurch Empfehlungen für den Einsatz in kritischer Infrastruktur getroffen werden können.**

***Stichworte*—Leistungselektronik, Hochstrom, Zuverlässigkeit, Wide-Bandgap-Halbleiter**

Nomenklatur

DUT	Device-under-Test
GaN	Galliumnitrid
IGBT	Bipolartransistor mit isolierter Gate-Elektrode
MOSFET	Metalloxid-Halbleiter-Feldeffekttransistor
SiC	Siliziumkarbid
USV	Unterbrechungsfreier Stromversorgung

https://doi.org/10.24405/14523

I. Einleitung

Die Leistungselektronik erlebt derzeit eine tiefgreifende Weiterentwicklung durch die breite Einführung von Leistungshalbleitern auf der Grundlage von Wide-Bandgap-Materialien. Dabei sind vor allem Bauelemente auf der Basis von Siliziumkarbid (SiC) und Galliumnitrid (GaN) von steigender Bedeutung. Für den Einsatz dieser neuen Technologie in kritischer Infrastruktur, ist die Zuverlässigkeit der Bauteile von größter Bedeutung. Besonderes Augenmerk liegt hierbei auf der Resilienz der Wide-Bandgap-Halbleiter in Bezug auf diverse Einflussfaktoren. Hierbei ist die exakte Kenntnis über die Betriebseigenschaften, die Aufbau- und Verbindungstechnik sowie der Ausfallmechanismen grundlegend [1]. Im Rahmen des Forschungsprojektes "Digitales Lebenszyklus-Monitoring, Härtung und Optimierung der Resilienz von Leistungselektronik in kritischer Infrastruktur" (DiMoLEK) wurden zu diesem Zweck neue Testumgebungen mit aktuellster Messtechnik aufgebaut. Weitergehend wurden moderne Geräte für die zerstörungsfreie Vor- und Nachuntersuchung von Bauteilen in Betrieb genommen. Der Fokus dieser Forschungsarbeit liegt dabei auf der dynamischen Charakterisierung von Siliziumkarbid-Bauelementen verschiedener Hersteller und Chiptechnologien. Mit diesen Ergebnissen ist es möglich, exakte Vorgaben für den idealen Arbeitsbereich der verschiedenen Halbleiter zu geben.

II. Entwicklung einer Testumgebung für Hochstrom Siliziumkarbid-MOSFETs

A. 1200 V *Siliziumkarbid-MOSFETs*

In dem Sektor der Hochleistungsanwendungen ist derzeit der Bipolartransistor mit isolierter Gate-Elektrode (IGBT) das Maß der Dinge, da dieses Bauelement eine gute Leitfähigkeit bei akzeptablen Schaltgeschwindigkeiten gewährleistet. Jedoch verfolgen einige Hersteller von Halbleiterbauteilen die Entwicklung von Metalloxid-Halbleiter-Feldeffekttransistoren (MOSFET) auf Basis von Siliziumkarbid. Durch die geringeren Schaltverluste der SiC-MOSFETs ergibt sich die Möglichkeit, die Schaltfrequenz zu erhöhen und somit die Größe von passiven Bauteilen innerhalb elektronischer Schaltungen zu reduzieren. Daraus lässt sich direkt eine erhöhte Leistungsdichte, reduziertes Gewicht, geringere Kosten und ein geringerer Kühlungsaufwand realisieren. Von großem Interesse ist dabei die Klasse mit einer Blockierspannung von 1200 V. Dies liegt darin begründet, dass diese Bauteilklasse in vielen verschiedenen Anwendungsgebieten zum Einsatz kommt. Dazu zählt unter anderem der Einsatz bei Solarwechselrichtern, Unterbrechungsfreier Stromversorgung (USV), Batterieantrieben oder industriellen Antrieben [3]. Mit Blick auf die Energiewende sind dies Schlüsseltechnologien, die mit einem verbesserten Wirkungsgrad und erhöhter Leistungsdichte effektiv den Kohlenstoffdioxid-Ausstoß minimieren können [4]. In diesem Projekt sollen verschiedene Halbleiter für Hochleistungsanwendungen im Bezug auf ihre Schalteigenschaften charakterisiert werden. Dabei werden SiC-MOSFETs der 1200 V Klasse in der Gehäusebauart TO247-4 mit Durchlasswiderständen $R_{\mathrm{DS(on)}} <= 20\,\mathrm{m}\Omega$ untersucht. Die Versuchsobjekte sind für die Verwendung bei Hochstromanwendungen geeignet, in denen bisher der IGBT zum Einsatz kam. Sie erlauben zum Teil den Gleichstrombetrieb mit Strömen $> 100\,\mathrm{A}$. In der modernen Leistungselektronik werden Leistungsschalter sowohl diskret, als auch in sogenannten Modulen mit mehreren, verschalteten Chips verwendet. Besonders bei hartschaltenden Topologien ist der Einsatz von SiC-MOSFETs durch die parasitären Induktivitäten des Gehäuses begrenzt, da die betriebssicheren Treiberbedingungen durch Gate-Oszillationen limitiert werden. Um dem Effekt entgegen zu wirken, verwendet das Gehäuse TO247-4, im Kontrast zu dem herkömmlichen TO247-3 Gehäuse, einen zusätzlichen Pin. Dieser separate niederinduktive Source Pin ermöglicht die Gate-Source Anbindung des Treibers mit einem Kelvin-Kontakt, dargestellt in Abbildung 1. Dadurch ist der Wert der parasitären Induktivität im Treiberpfad, welche auf das Gehäuse zurückzuführen ist, im Verhältnis zu den anderen parasitären Einflüssen im elektrischen Kreis verhältnismäßig gering [2].

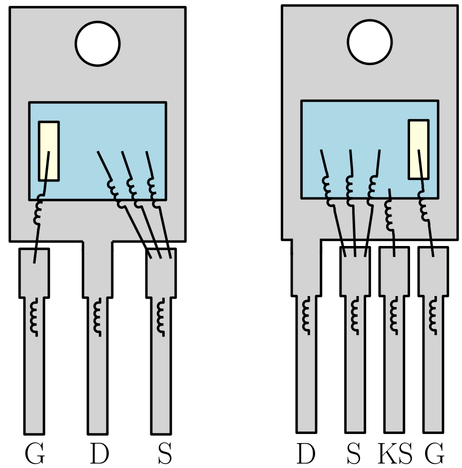


Abbildung 1. Aufbau Gehäusetyp TO247-3 und TO247-4.

B. *Aufbau der Testumgebung*

Für den Vergleich der hochleistungsfähigen SiC-MOSFETs unter den angestrebten Betriebsbedingungen ist eine zuverlässige Testumgebung zwingend erforderlich. Diese muss neben dem Testen der vom Hersteller maximal gewährleisteten Arbeitsbedingungen, eine Ansteuerung aller Schalter, entsprechend der Empfehlungen im Datenblatt, ermöglichen. Damit die Schalter innerhalb einer Reihenuntersuchung untereinander verglichen werden können, ist es wichtig, dass innerhalb der Versuchsreihe kein Wechsel der Messumgebung vollführt wird. Dies würde bei den schnellen Schaltvorgängen aufgrund der Einflüsse des elektromagnetischen Feldes zu deutlichen Abweichungen zwischen den Messungen führen. Bei der Entwicklung und dem Aufbau der Messumgebung wurde daher darauf geachtet, durch ein robustes Design der Doppelpulsplatine, sowie eine adaptive Treiberschaltung eine Vergleichbarkeit zu gewährleisten.

C. *Anforderungen und Design einer hochleistungsfähigen Doppelpulsmessplatine*

Die Standardtestmethode für die dynamische Charakterisierung leistungselektronischer Schalter ist die Verwendung des sogenannten Doppelpulstests. Bei diesem Versuch wird der Schalter, welcher charakterisiert werden soll, in einer Halbbrückenanordnung, wie in Abbildung 2 zu sehen ist, verschaltet.

Bei Untersuchungen an MOSFETs wird das Testobjekt, englisch Device-under-Test (DUT), typischerweise sowohl auf der High- (T_{HS}) und Lowside- (T_{LS}) Position eingebaut, um einen Bezug zur realen Verwendung herzustellen. In der Abbildung 2 ist zu erkennen, dass parallel zu dem Highside-Schalter eine Lastinduktivität L_{Last} geschaltet wird. Während die Gatespannung, welche an den Highside-Schalter T_{HS} angelegt wird, den Schalter für die gesamte Messdauer im blockierenden Zustand halten soll, wird auf dem Gatekontakt des Lowside-Schalters ein Pulsmuster angelegt, welches den Schalter zwei Mal ein- und wieder ausschaltet. Dadurch ist es möglich, den Aus- und Einschaltvorgang bei einem von

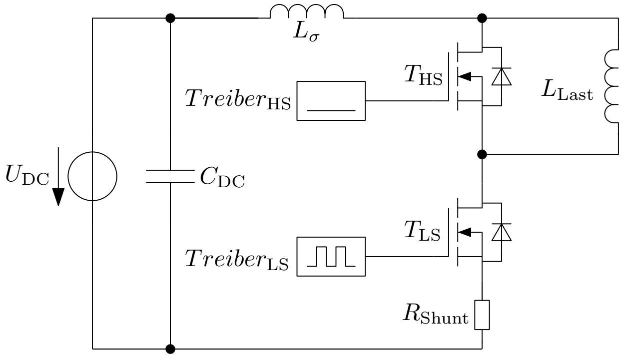


ABBILDUNG 2. HALBBRÜCKENVERSCHALTUNG FÜR DOPPELPULSMESSUNGEN.

der Pulslänge abhängigen Strom zu untersuchen. Besondere Herausforderung beim Design der Doppelpulsplatine ist der Aufbau eines niederinduktiven Kommutierungskreises L_σ bei gleichzeitig funktionaler Positionierung der Messobjekte. Da für die Vermessung von SiC-Bauteilen insbesondere die temperaturabhängige Charakterisierung von Bedeutung ist, wurde bei diesem Design ein Fokus darauf gelegt, die Bauteile so zu platzieren, dass diese sehr einfach mit einem Temperierungsgerät verbunden werden können. Damit dennoch ein niederinduktives Design realisiert werden konnte, wurde eine 6-lagige Leiterplattenstruktur gewählt. Dies hat zum einen den Vorteil, dass die zum Teil sehr hohen Testströme ohne Probleme von der Platine getragen werden können und zum anderen ist durch die hohe Anzahl der Lagen eine gute Anbindung des Zwischenkreises und der nötigen Messmittel möglich. ABBILDUNG 3 zeigt exemplarisch die bauteilnahe Struktur der äußeren Lagen.

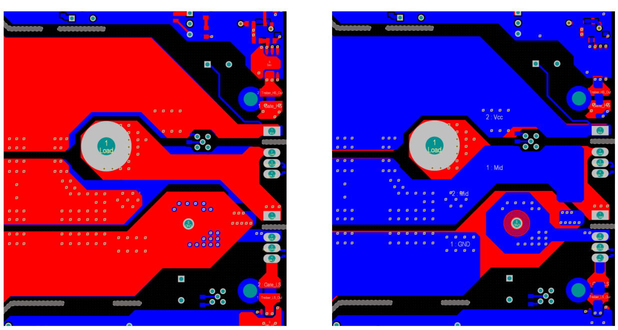


ABBILDUNG 3. STRUKTUR DER KUPFERFLÄCHE IN DER OBEREN UND UNTEREN UNTER LAGE.

Eine weitere Maßnahme, welche für den Aufbau eines niederinduktiven Kommutierungskreises genutzt wurde, ist die Verwendung niederinduktiver Kondensatoren im Zwischenkreis, kombiniert mit der Implementierung eines Plattenkondensators im Lagendesign der Platine. Als Lastinduktivität wird eine extrem niederkapazitive Luftspule verwendet. Diese zeigt bis zu einer Stromstärke von 1000 A nachgewiesen kein Sättigungsverhalten. Das Resultat der aufwendigen Prüfeinrichtung ist ein sehr geringer Einfluss des Aufbaues auf das Messergebnis. Damit ist es möglich die verschiedenen Bauteilcharakteristiken in hoher Qualität auszuwerten und zu vergleichen.

D. Adaptives Treiberdesign

Das übergeordnete Ziel bei der Auslegung und dem Design des Treibers ist es, den MOSFET zuverlässig ein- bzw. auszuschalten. Hierbei ist es wichtig, dass das Referenzpotential des Treibers auf dem Source-Potential des jeweiligen Schalters liegt. Besondere Aufmerksamkeit bedarf des Potentials des Highside-Schalters T_{HS}, denn je nach Schaltzustand wechselt das dazugehörige Bezugspotential. Bei der Entwicklung des Treibers ist es deshalb wichtig, parasitäre Kapazitäten, bedingt durch den Lagenaufbau der Platine, so klein wie möglich zu designen. Diese Kapazitäten müssen bei jedem Schaltvorgang um den Betrag der Zwischenkreisspannung umgeladen werden. Für die hier vorgestellte Platine wurde dies durch den Einsatz von zwei galvanisch getrennten Versorgungen für den High- $Treiber_{HS}$ und Lowside Treiber $Treiber_{LS}$ realisiert. Jene befinden sich jeweils mit einer eigenen Potentialinsel auf einem abgegrenzten Bereich auf der Platine. Dadurch werden Überlagerungen mit den Ebenen des Zwischen- und Kommutierungskreises verhindert. Da die diversen SiC-MOSFETs der 1200 V Klasse unterschiedliche Gate-Source Spannungen für die Ansteuerung benötigen, wurde der Treiberkreis so entwickelt, dass diese Spannung ohne die Neubestückung von Bauteilen über Potentiometer hochpräzise verstellt werden kann. Der verwendete Gate-Treiber IC bezieht sein Schaltsignal von einem sehr schnellen kapazitiven Trennverstärker. Für die niederohmigen SiC-MOSFETs liegt aufgrund der großen Chipfläche eine entsprechende große Gate-Source Kapazität vor. Deshalb wurde ein extrem leistungsfähiger Treiber ausgewählt, welcher in der Lage ist, Spitzenströme von 14 A bereitzustellen und damit jeden, in dem Projekt zu untersuchenden Leistungshalbleiter mit seiner maximalen Schaltgeschwindigkeit schalten kann. Somit ist die entworfene Doppelpulsplatine in der Lage jeden in diesem Forschungsprojekt zu untersuchenden Wide-Bandgap-Leistungshalbleiter entsprechend seiner optimalen Betriebsbedingungen zu betreiben und charakterisieren. Damit ist ein realistischer und zuverlässiger Vergleich der unterschiedlichen Schalter in der Reihenuntersuchung möglich. ABBILDUNG 4 zeigt exemplarisch ein Foto des Lowside-Treiberkreises.

E. Messmittel und wichtige Parameter der Auswertung

Für die präzise Auswertung und Messung von immer schneller werdenden Schaltvorgängen und zunehmenden Flankensteilheiten ist die Auswahl der Messmittel und die sorgfältige Platzierung innerhalb der Messumgebung von großer Bedeutung. Um eine qualitativ hochwertige Charakterisierung der SiC-MOSFETs zu erhalten, ist sowohl eine hohe Auflösung des Messsignals, als auch eine sehr hohe Aufnahmegeschwindigkeit von Bedeutung. Für die Auswertung des Schaltverhaltens müssen der Drainstrom und die Spannungsabfälle Gate-Source und Drain-Source auf dem Lowside und ein Highside Schalter entsprechend genau erfasst

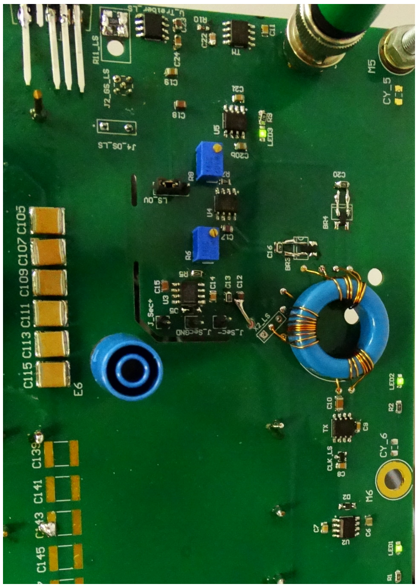


ABBILDUNG 4. FOTO ADAPTIVER LOW-SIDE-TREIBER.

werden. Das 6-lagige Leiterplattendesign ist auch hier ein Vorteil und reduziert die Störeinkopplung sowie mögliche parasitäre Rückwirkungen auf die Messsignale deutlich. Mit den zusätzlichen Lagen ist es möglich, die Messabgriffe nah an den DUTs zu platzieren sowie die Hin- und Rückführungen von Messsignalen passend übereinander zu führen. Dadurch wird die Induktivität in den Messpfaden deutlich reduziert. Neben der Vermeidung von Störeinflüssen innerhalb der Leiterplattenstruktur gilt es die richtigen Messmittel für die hochdynamischen Schaltvorgänge zu wählen. ABBILDUNG 5 zeigt die Messabgriffe an der Platine. Für die Messung des

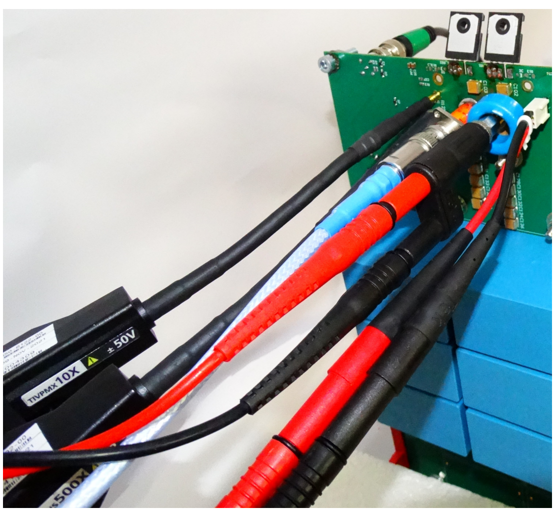


ABBILDUNG 5. MESSABGRIFFE FÜR DIE MESSUNGEN AN DEN LEISTUNGSBAUELEMENTEN.

Stromes ist im Design die Anbindung eines koaxialen Shunts vorgesehen. Obwohl dieser für den Kommutierungskreis eine zusätzliche Induktivität von mindestens 5 nH bedeutet, ist die hohe Bandbreite von mehr als 1 GHz wichtig für die Auswertung des Schaltverhaltens [5]. Die Spannung wird mit optisch isolierten Tastköpfen gemessen. Diese bieten eine sehr gute Unterdrückung von Gleichtaktstörungen und eine hohe Bandbreite von bis zu 1 GHz. Außerdem zeichnen sie sich durch sehr kleine Fehlertoleranzen bei Messungen ohne festes Bezugspotential aus, das heißt auch bei hohem Bezugspotential können kleine Spannungen, wie Gate-Source Spannungen, präzise ausgewertet werden. Für die Gate-Source Spannung des Low- und Highside Schalters werden dafür MMCX Anschlussstecker verwendet. Diese Stecker sind bis zu 170 V effektiv spezifiziert. Für die Drain-Source Spannung reicht dies dementsprechend nicht aus. Dort werden Stiftleisten mit einem Abstand von 5.08 mm verwendet, womit die Isolation sichergestellt ist. Für beide Anschlüsse steht bei dem optischen Tastkopf ein passender Aufsatz zur Verfügung [6]. Alle Messungen werden mit einem Oszilloskop, welches eine Bandbreite von 2.5 GHz für alle Kanäle zur Verfügung stellt, durchgeführt [7], dargestellt in ABBILDUNG 6.

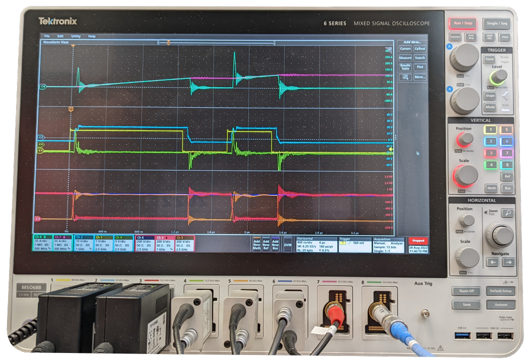


ABBILDUNG 6. VERWENDETES OSZILLOSKOP MIT MESSANSCHLÜSSEN.

III. ERSTE MESSUNGEN UND AUSBLICK

A. *Inbetriebnahme*

Zur Gewährleistung eines stabilen Messsystems gilt es die Bestandteile der Messumgebung ausführlich zu testen und in Betrieb zu nehmen. In dieser Anwendung sind dabei die folgenden Vorarbeiten von elementarer Bedeutung:

- Kalibrierung der verschiedenen Tastköpfe
- Funktionstest der Treiberschaltung mit ihrer Versorgung
- Charakterisierung der gewählten Lastinduktivität
- Kontrolliertes Hochfahren der Zwischenkreisspannung
- Anpassen der Doppelpulslänge um die erzielten Testströme anzufahren

Vor der Nutzung des Oszilloskops mit den unterschiedlichen Tastköpfen werden diese entsprechend ihrer Verwendung bei der Messung eingestellt. Dies gewährleistet einen Schutz der Geräte und stellt eine zeitlich korrekte Erfassung der unterschiedlichen Signale sicher. Für den Funktionstest der Lowside- und Highsidetreiberschaltung wird die Versorgung und galvanische Trennung zwischen Primär- und Sekundärseite betrachtet. Danach wird, noch ohne die Bestückung von tatsächlichen Leistungshalbleitern und mit entladenem Zwischenkreis, eine Ansteuerung mittels Funktionsgenerator durchgeführt und gemessen. Abschließend wird ein Leistungstest mit Kondensatoren, ausgelegt auf die Kapazität der DUTs, durchgeführt um sicherzustellen, dass der Treiber stabil arbeitet. Diese Schritte wurden erfolgreich für den Aufbau durchgeführt. ABBILDUNG 7 zeigt die Spannung $V_{\mathrm{GS_{LS}}}$ bei einem angelegten Taktsignal, dabei werden die für das Ein- und Ausschalten eingestellten Spannungen erreicht.

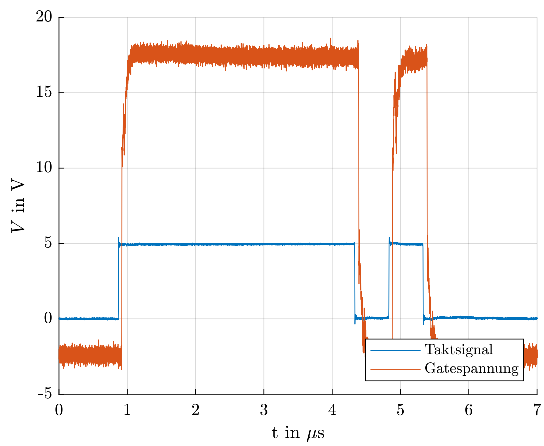


ABBILDUNG 7. VERLAUF DER AM TREIBER ANGELEGTEN TRIGGERSIGNALSPANNUNG UND DER RESULTIERENDEN GATESPANNUNG.

Die Charakterisierung der gewählten Lastinduktivität wurde mit einem Choketester sowie einem LCR-Meter durchgeführt. Mit dieser redundanten Messung kann zum einen überprüft werden, ob die Induktivität ein Sättigungsverhalten zeigt und zum anderen kann das exakte Verhalten bei unterschiedlichen Betriebsfrequenzen analysiert werden. Aus der ABBILDUNG 8 geht hervor, dass die Lastinduktivität eine Strombelastung von bis zu 1000 A stabil führen kann und somit keine Sättigung in der Induktivität hervorgerufen wird. Dieser Wert liegt deutlich oberhalb der im Versuchsaufbau zu erwartenden maximalen Ströme.

Um die Platine endgültig in Betrieb zu nehmen, werden Leistungshalbleiter auf den entsprechenden Positionen verbaut und der gesamte Aufbau inklusive der Messinstrumente in einer sicheren Umgebung platziert. Mit einem kontrollierten Hochfahren der Zwischenkreisspannung wird die Funktionalität der Platine geprüft. Abschließend werden die Pulslängen bei der für den Test ausgewählten Zwischenkreisspannung von 800 V für die Einstellung der anvisierten Testströme eingestellt. Die ABBILDUNG 9 zeigt beispielhaft den Verlauf der Drain-Source-Spannung am DUT und den Durchlassstrom für einen Doppelpuls mit Aus- und Einschalten bei 200 A.

In der ABBILDUNG 9 ist zu erkennen, dass es mit der finalen Testumgebung möglich ist, Testströme von 200 A zuverlässig zu erzeugen und die notwendigen Messungen an dem DUT mit hoher Bandbreite durchzuführen.

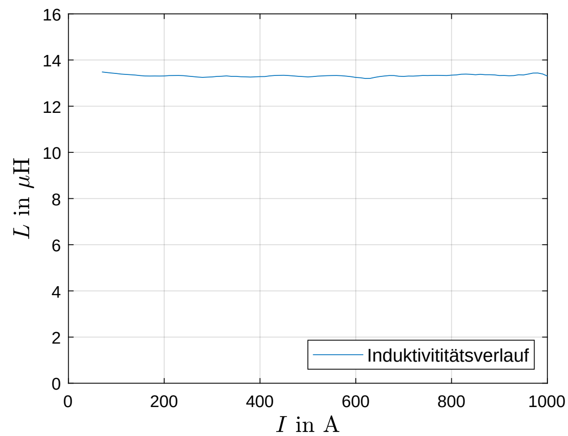


ABBILDUNG 8. MESSUNG DER LASTINDUKTIVITÄT UNTER ERHÖHUNG DER STROMBELASTUNG.

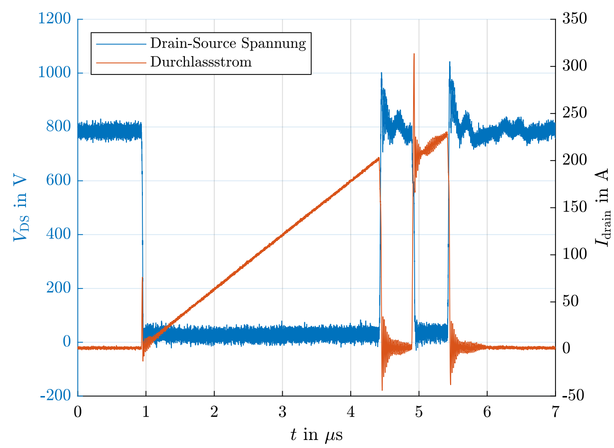


ABBILDUNG 9. DOPPELPULSVERSUCH BEI EINEM TESTSTROM VON 200 A.

IV. AUSBLICK

Für die Reihenuntersuchung der dynamischen Eigenschaften leistungselektronischer Bauelemente wird die Testumgebung um ein Prozessthermostat erweitert. Besonders bei hohen Temperaturen verändert sich das Verhalten von Wide-Bandgap Halbleitern deutlich im Vergleich zum Betrieb bei 25 °C. Um jedoch eine umfassende Charakterisierung durchzuführen reicht es nicht aus, das Schaltverhalten zu untersuchen. Bei dem Forschungsprojekt DiMoLEK wird ein großer Fokus darauf gelegt, Fehlermechanismen zu identifizieren und Parameter für deren frühzeitige Detektion zu erforschen. Zu diesem Zweck befinden sich weitere Teststände in der Entwicklung. Drei Teststände sind dabei hervorzuheben:

- Lastwechselteststand: Teststand für die Untersuchung der Ausfallmechanismen bei langer, dauerhafter Benutzung von Halbleitern.
- Hochspannungs-Kennlinienschreiber: Exakte Untersuchung der Isolationseigenschaften und Identifikation auftretender Leckströme.

- Kurzschlussteststand: Bestimmung der Kurzschlussfestigkeit von Leistungshalbleitern bei fehlerhaften Schaltimpulsen.

Die Analyse der Fehlermechanismen wird dabei unterstützt durch bildgebende Messinstrumente. Mit diesen ist es möglich, exakte Erkenntnisse über den inneren Aufbau der Bauelemente zu gewinnen und bei Fehlerfällen den Mechanismus des Fehlers innerhalb der Struktur des Halbleiters zu analysieren. Für jedes Testobjekt kann dadurch eine zerstörungsfreie optische Voruntersuchung durchgeführt werden und im Anschluss an den Ausfall mit dem resultierenden Fehler verglichen werden. ABBILDUNG 10 zeigt Bilder von dem Chip und den Bondungsdrähten eines SiC-MOSFETs im TO247-4 Gehäuse.

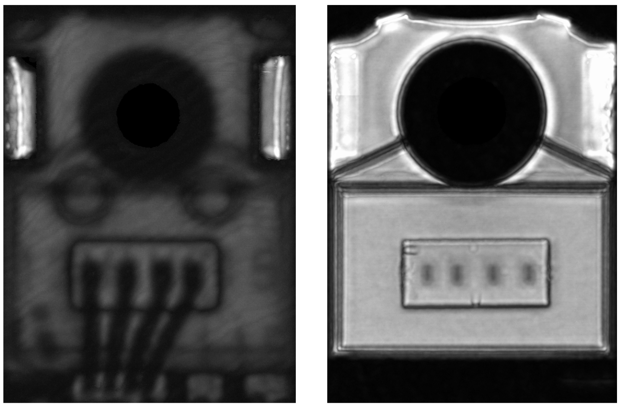


ABBILDUNG 10. ULTRASCHALLAUFNAHMEN DER BONDUNGSDRÄHTE, LINKS, UND DER CHIPFLÄCHE, RECHTS, EINES SIC-MOSFETS IM TO247-4 GEHÄUSE.

Parallel zu den direkten Messungen am Halbleiter ist es von steigender Bedeutung, das elektrische Feldverhalten des Halbleiters im Kontext der gesamten Betriebsumgebung zu erforschen. In Anwendungen der kritischen Infrastruktur darf kein Fehler in anderen Bauelementen, ausgelöst durch den Betrieb der Leistungselektronik, auftreten. Dafür werden Simulationen zur exakten Feldbestimmung innerhalb kritischer Anwendungen durchgeführt. Dies ermöglicht es, den optimalen Betriebsbereich der neuen WBG-Leistungshalbleiter zu erforschen und zeitgleich ein robustes System aufzubauen, welches gegen kritische Feldüberhöhungen geschützt ist.

Der enorme Anstieg der Schaltgeschwindigkeit mit der breiten Einführung neuer Wide-Bandgap-Halbleiter hat ebenso weitreichende Folgen auf die Elektromagnetische Verträglichkeit (EMV) der Leistungselektronik. Um sicherzustellen, dass kritische Systeme sowohl gegen Störungen von außen, als auch gegen innere Störungen geschützt sind, werden hochpräzise Messungen, angelehnt an geltende Normen, in EMV-Kammern durchgeführt. Mit diesen Messungen ist es möglich, eine exakte Nachbildung der wirkenden Parameter innerhalb einer Simulationsumgebung zu entwickeln. Somit können Vorhersagen über mögliche Fehlerfälle getroffen werden und Abhilfemaßnahmen, wie beispielsweise die passende, schützende Schirmung oder elektrische Filter entwickelt werden.

V. FAZIT

Im Zusammenhang des Forschungsprojektes wurde eine hochkomplexe Testschaltung für die dynamische Charakterisierung aktueller Siliziumkarbid-Bauelemente in Betrieb genommen. Mit der Testschaltung ist es gewährleistet, bis zu sehr hohen Strömen zuverlässige, hochauflösende Messergebnisse zu erzielen. Mit der Auswertung dieser Messergebnisse ist es möglich, die Fragestellung nach der Beanspruchung der Halbleiter während der Schaltvorgänge und daraus folgend die korrekte thermische Auslegung für den Betrieb in kritischer Infrastruktur zu beantworten. Basierend auf dieser Grundlage können im Rahmen des Forschungsprojektes weitreichende Untersuchungen in verschiedenen Fachrichtungen durchgeführt werden. In Kombination ebnen diese den Weg für ein digitales Lebenszyklus-Monitoring robuster Leistungselektronik in kritischer Infrastruktur.

DANKSAGUNG

Die Forschungsarbeit “Analyse und Charakterisierung aktueller Siliziumkarbid-Bauelemente für ein digitales Lebenszyklus-Monitoring robuster Leistungselektronik in kritischer Infrasturktur” des Forschungsprojektes “DiMoLEK” wird durch das dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr gefördert.

LITERATUR

[1] D. Schröder, R. Marquardt, Leistungselektronische Schaltungen Funktion, Auslegung und Anwendung, 4. Auflage, Springer Vieweg, 2019.

[2] J. Smutka, V. Scarpa, J. Svetlik, J. Hajek, Improvement of Dynamic Characteristics of discrete 1200V SiC MOSFETs through Kelvin Source connection, PCIM Europe digital days 2020, 2020.

[3] D. Peters, T. Aichinger, T. Basler, W. Bergner, D. Kueck, R. Esteve, A Treatise on Electricity and Magnetism, 1200V SiC Trench-MOSFET Optimized for High Reliability and High Performance, Materials Science Forum, 2017.

[4] I. Omura, Power Electronics for a Future Sustainable Society, PCIM Europe, 2022.

[5] Nexperia, MOSFET & GaN FET Application Handbook A Power Design Engineer’s Guide, www.nexperia.com, 2020.

[6] Tektronix, Isolierte Messsysteme TIVP1, TIVP05, TIVP02 Datasheet, www.tek.com, 2021.

[7] Tektronix, 6 Series MSO Mixed Signal Oscilloscope Datasheet, www.tek.com, 2022.

Computerized Refurbishment

Frank Gärtner, Alexander List, Sören Nielsen, Hongjian Wu, Zahra Arabgol, Levke Wiehler, Julio Gutiérrez de Frutos, Chunjie Huang, Thomas Klassen
Institute of Materials Science
Helmut Schmidt University
Hamburg, Germany
*frank.gaertner@hsu-hh.de

Marcel Lewke, Alexander Fay
Institute of Automation Technology
Helmut Schmidt University
Hamburg, Germany
*marcel.lewke@hsu-hh.de

Dhruvit Rashikbhai Gabani, Jens Gibmeier, Astrid Pundt
Karlsruhe Institute of Technology
Karlsruhe, Germany

Tiago Werner, Kai Hilgenberg, Mauro Madia, Thomas Böllinghaus
Bundesanstalt für Materialforschung und –prüfung
Berlin, Germany

Leonhard Holzgaßner, Peter Richter
Impact Innovations GmbH
Haun/Rattenkirchen, Germany

Nils Clausing, Henry Loitz
H.LoitzRobotik,
Hamburg, Germany

Philipp Keuter, Moritz to Baben
GTT-Technologies
Herzogenrath, Germany

Markus Steierl, David Erich Schimbäck, Thorsten Rösler
Airbus Defence and Space GmbH
Manching, Germany

Holger Debuch, Thomas Gartner
Lufthansa Technik AG
Hamburg, Germany

***Abstract* – High performance aerospace parts are typically scrapped and replaced, as soon local damages exceed certain tolerances, because available classical repair techniques so far fail to guarantee required part strengths. As solid state deposition technique, cold spraying offers the potential for restoring damaged areas to original shape while retaining part properties, thus saving costs and conserving resources. So far, however, the needed efforts are high and thus costly: process parameter sets, robot kinematics as well as pre- and post-processing must be individually adjusted and controlled. For easier process adoption, a holistic concept is developed that includes all critical individual boundary conditions, i.e. analysis and categorizing of defects, pre-machining, repair, and post-treatment in one digital description and computerized process chain. By that, the required part properties profile can be guaranteed even for batch size one. The concept includes developing the algorithms for an integrated manufacturing environment as well as for collecting needed experimental input data. The complex interplay of influences is addressed by an interdisciplinary engineering approach involving materials science, fluid mechanics and automation technology. Finally, the collaboration with industrial partners will allow for a fast transfer into real production environments.**

Keywords – Cold Spray, Repair, Additive Manufacturing, Influence of Spray Parameters, Industrial Robot

I. INTRODUCTION

Mankind's challenges to reduce resource consumption have to include concepts for sustainable material cycles like circular economy and cradle-to-cradle [1, 2]. Resource-conserving processes for energy saving and production as well as material cycles are in focus of world-wide development and on production side aim for adopted designs of consumer products and industrial goods. For both, refurbishment instead of replacement is a first step into the right direction, but has to tackle all safety measures. Particularly, components in the aerospace industry have to comply with strict regulations to guarantee flight safety. Respective requirements demand structural robustness of the components as well as tight tolerance limits against damage due to corrosion or wear during operation. Moreover, the production of large aerospace components is often complex and cost-intensive. Nevertheless, in aviation industries, even minor defects regularly force components to be taken out of service and replaced. In contrast, suitable repair processes for reconditioning of these components would significantly reduce costs and save production time as well as resources.

FIGURE 1. EXAMPLE OF A ROBOT-GUIDED REPAIR APPLICATION OF COLD SPRAY [3].

In order to obtain an optimum repair result that fulfills the highest requirements regarding material properties, simple geometric shape restoration is not sufficient. Usually in repair, applied additive manufacturing techniques result in particular microstructural features, possible defects and respective – potentially even anisotropic – mechanical properties. Systematical tailoring of microstructures and properties to the specific component and geometry requires complex routines. This work proposes the design of an automated cold spray repair system that facilitates a complete individual repair procedure for aircraft components.

https://doi.org/10.24405/14524

Additive Manufacturing (AM) as a repair method is a step forward towards a more sustainable production economy and enables extending the product life by repair of damaged components [4]. Various processes have demonstrated the suitability in this regard, such as direct energy deposition and gas tungsten arc welding [5, 6]. However, these processes use a direct heat source, e.g. a laser or arc beam, to melt the material to be deposited. Consequently, the substrate component is also subject to a temperature rise, resulting in microstructure modification or phase transformations, potentially even to the liquid state. Also, incorporation of oxides is likely, which are critical for crack initiation and failure. Thus, the challenge of repairing oxidation-sensitive components with low temperature input under ambient conditions remains.

In recent years, cold spraying (CS) has emerged as a promising technology for repair applications, particularly for oxidation-sensitive materials. As compared to other processes, cold spray (CS) has shown advantages in the field of repair due to unique component properties by retaining the phase composition and reaching high deposit strengths. In CS, material is deposited in solid state. Powder material is accelerated in a pressurized and heated process gas stream (e.g. nitrogen or helium) that passes through a de Laval type nozzle. Particles then impact on the substrate with supersonic velocity and deform plastically. This results in a temperature rise localized in the interface area up to temperatures close to the melting point. Thermal softening, and adiabatic shear instabilities in the interface then facilitate metallic bonding without melting. The main advantages of CS concern the high deposition rate, the absence of solidification and comparably low process temperatures, making CS an interesting technology for processing of oxidation-sensitive materials (e.g. aluminum- and titanium-alloys) [7, 8]. However, the properties of the deposited layers are strongly dependent on initial powder conditions, process parameter sets and on geometric influences, such as the deposition angle [9]. Thus, optimum solutions require detailed knowledge about all individual influences and also about possible inter-dependencies.

Current research in the field of CS repair focuses on two distinct topics: repair of the original shape of the component by additive manufacturing (AM) and optimizing the material properties of the component. Nonetheless, the combination of both research topics is necessary to obtain the best repair result and is consequently pursued in this work. In the literature already different attempts are reported for solving the challenges for the use of CS as possible additive manufacturing or repair technique. In [10] the authors investigate the use of CS for restoring parts containing cracks and to analyze the crack resistance of such repaired components. An aluminum alloy plate with a 30° V-notch on its surface is repaired by cold spraying of aluminum alloy powders. The results indicate that the repaired panels have up to sixfold increased crack growth resistance as well as an increased global fatigue life in comparison to the original component containing the defect. However, the proposed process of crack repair might still be enhanced since the existing sharp flank angle of 30° is non-optimum and could result in lower deposit quality. Results of the work in [11] illustrate the influence of the spray angle on the obtained deposition efficiency and porosity. Starting from a spray angle of 90° to the substrate surface, the deposition efficiency is over 95 % and the porosity is 0.13 %. A decrease of the spray angle to 45° results in a drop of the deposition efficiency to 83 % and an increase in porosity to more than 6 %. Thus, optimum repair conditions of defects should also consider pre-processing to adjust the geometry with respect to the ideal process characteristics of CS. The authors of [12] demonstrate the successful application of a portable CS repair system to repair damaged aluminum components. The investigations include pre-processing, CS application, post-processing and performance tests (adhesion, fatigue, and corrosion). The use of the portable system indicates some disadvantages, such as inaccuracies in process repeatability and restrictions to lower process gas temperature and pressure, which results in limited CS deposit qualities than attainable with a stationary repair system. The authors of [13] propose CS of aluminum to repair an internal bore of a navy valve actuator. The defined requirements for the repair are a maximum of 5 % porosity on critical surfaces and a minimum of 68.9 MPa adhesion strength, as attainable in standardized pull-off tests. The results prove the successful repair in accordance with the required properties. An average porosity of 3 % and an average adhesion strength of 71.4 MPa are achieved in this particular case. However, details regarding variations of defect category and respective scatter of the mechanical properties are not provided. More recently, in [14] the authors present a CS repair framework that consists of a 3D scanning system, a defect database and a CS additive repairing system. The 3D scanning system provides information about the component's individual damage, which is then categorized to a typical standard flaw within the database, and a standard repair process is applied accordingly. The CS additive repair system includes programming, simulation and material deposition. Although the work includes the full geometric shape restoration of the damaged area, issues related to respective optimum deposit properties to meet high performance requirements are not considered. In addition, the use of standardized defect layouts in a database cannot provide optimum repair to all sorts of defects with a variety of different, often complex shapes and varying depths.

Previous work on the optimization of cold spraying chiefly considered the main parameters given by gas temperature and pressure. However, in reality, the situation is more complex, despite the – in first view – rather simple relation. The performance of a deposit depends on the effective ratio η between particle impact velocity v_p and critical velocity v_{cr}. However, respective effects by (i) particle size on v_p, as well as (ii) mechanical particle properties in as delivered or modified states, (iii) incident deposition angle or even (iv) substrate surface temperature on v_{crit} could have similar influence on deposit properties as primary parameter sets [11, 15–20]. In particular, the surface temperature is further influenced by the gas temperature, the stand-off distance between nozzle exit and substrate, by the robot trajectory and transverse velocity, as well as by the geometry of the component and by the thermal effusivity (i.e. heat capacity and heat conductivity combined) of the substrate material. In addition, peening effects and surface temperatures determine internal stresses [21]. In addition, (iv) surface topographies and properties (roughness and hardness) by respective substrate pre-treatment determine deposit adhesion and thus overall performance of repaired parts. Since CS of high-performance materials like titanium- and aluminum-alloys already operates at upper technical limits, an understanding of all these different influences is needed to reach the thresholds for technical applications. For staying within geometrical boundary conditions like position and angle of the nozzle in relation to the work piece, industrial robots should be used to control the movement with high precision and repeatability to allow for individual repair of complex parts. FIGURE 1 depicts the example of a robot-guided cold spray application, showing the repair of a propeller blade [3].

In order to incorporate all the different, individual dependencies and their complex interplay into one uniform description, an integrated, automated CS concept is needed. In ideal, such should be incorporated into one common digital environment. For following all these parallel paths, the project aims to develop an integrated CS system that includes (i) reverse engineering to analyze, classify and generate digital data of the damaged component, (ii) digital incorporation of thresholds for CS parameter tuning and geometrical boundary conditions, (iii) pre-processing for guarantying needed geometries for the CS process, (iv) adjusting of surface topographies, (v) toolpath planning to optimize robotics for the CS process, (vi) on-line monitoring to ensure process quality, (vii) post-processing and (viii) performance testing of material properties to meet the challenging requirements of aerospace industries. Apart from deposit production, for aerospace repair applications dealing with a batch size of one, also sophisticated methods are needed for non-destructive quality inspection.

Taking Al-and Ti-alloys as examples, the strategies to reach thresholds for aerospace applications by CS repair are given in the following as well as first results on the different paths of development.

II. PARAMETERIZATION OF INFLUENCES ON DEPOSIT PROPERTIES

Most influences on deposit qualities can be expressed in terms of the particle velocity v_p to critical velocity v_{crit} ratio η. This enables to define most suitable parameter sets and particle sizes for reaching high impact velocities. The deposition of Al-and Ti-alloys already operates at upper technical limits of CS. Nevertheless, numerical simulations are under investigation to improve particle velocity and temperature by feedstock specific nozzle designs and alternative nozzle materials that enable better process stability without nozzle clogging. Measures for a more precise definition of the critical velocity concern investigations of powder strengths. Possible powder modifications aim for reducing feedstock strengths to enable better bonding.

Higher effective surface temperatures of the part support bonding and could ensure better deposit qualities. However, a systematic description of respective influences on the critical velocity still needs simulation supported analyses. Moreover, despite locally higher spot temperatures being beneficial for bonding, associated temperature gradients could cause intrinsic deposit stresses. Respective influences are explored by modelling of the temperature distribution for varied heat flux under individual trajectory speeds applied by the robot system and experimentally determined stresses.

Further improvement of deposit qualities can be obtained by thermal or mechanical post treatments. Both is investigated under the view to minimize possible overaging effects of the component under repair.

Thresholds for pre-machining as well as robot toolpath planning are estimated by η roughly scaling with the sine of impact angle. Moreover, the trajectory speeds during deposition then determine local heating time under the spray spot and thus surface temperatures, and therefore should be kept with certain ranges. Both determine thresholds for the robot kinematics used for repair.

All the different influences are validated by experimental analyses of deposit microstructures and properties. These investigations are accomplished by non-destructive tests to derive correlations to direct analyses of material properties. As such, the results of non-destructive analyses like conductivity must be developed into correlation functions to real deposit properties as provided by mechanical tests, and supported by simulations.

To meet all these requirements, an integrated automated cold spray repair has to combine the simulative representation of the process as well as the in-situ process control, both then ensuring a continuous quality.

III. AUTOMATED COLD SPRAY REPAIR SYSTEM

This section provides an overview of an integrated CS repair system. In the project, the automated repair by CS is applied to damaged aircraft components. FIGURE 2 illustrates the setup of the robotic cell exemplary in the state of material deposition. The system contains a powder feeder, a high-pressure gas supply, a gas heater, a spray gun with a de Laval nozzle and the robot framework with the industrial robot, the robot controller as well as the operating computer. The CS gun, the pre-processing tool and the sensors are mounted on the end effector of the industrial robot. Control of the repair process is provided by simulation-based algorithms interfaced with the operating industrial robot.

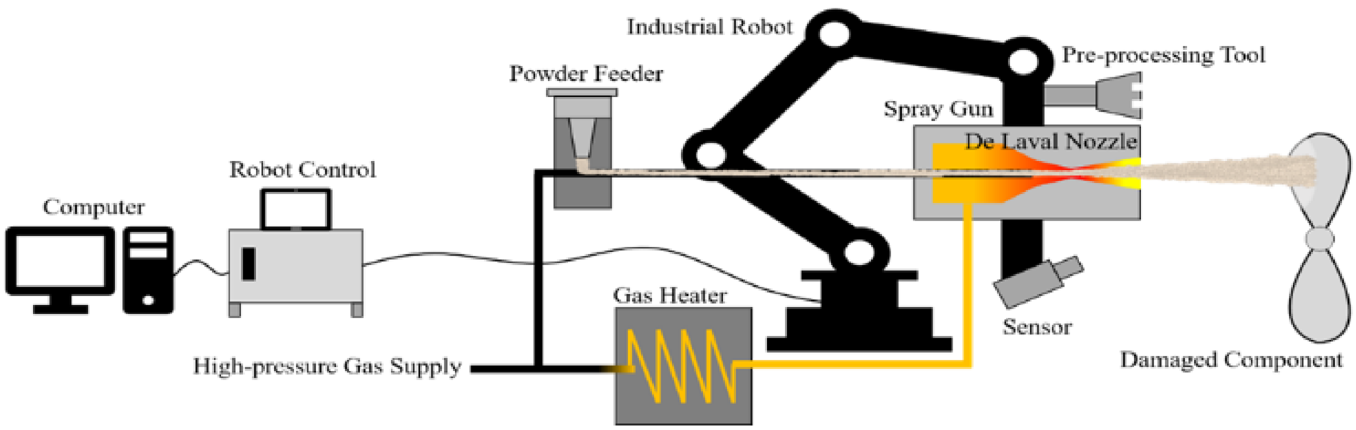


FIGURE 2: SETUP OF THE ROBOTIC COLD SPRAY CELL [22].

The general workflow is schematically illustrated in FIGURE 3 for the example of a propeller with a corrosion damage. Based on the existing corrosion damage, the component and the damaged area are analyzed using sensors. The simulation-based algorithms determine the pre-machining to be applied and the optimum spray toolpath. Here, the suitable material removal for the existing geometry volume and the subsequent optimal spray toolpath (including the optimized process conditions for CS) are determined. Beginning with the realization of pre-machining by milling, the complete removal of damaged material is ensured, as well as the creation of conditions for the subsequent material deposition. Afterwards, the machined damage is refilled by applying the optimized spray toolpath via CS so that the material properties meet the required specifications. To successfully complete the repair process, post-processing by e.g. milling is performed.

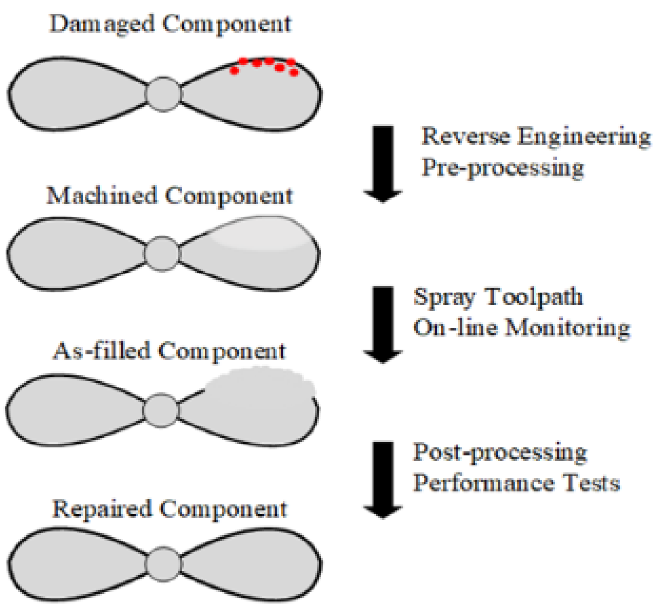


FIGURE 3: REALIZATION OF THE REPAIR PROCESS FOR AN EXEMPLARY CORRODED PROPELLER COMPONENT [22].

The complete repair process flow for developing automated repair by CS is illustrated in FIGURE 4. For a given deposit material, the parameterization of cold spray parameter sets and boundary conditions are supplied as input data (data base, sub-routines). Starting from a damaged component, the first process step concerns analyzing and classifying the damage and the component via reverse engineering using sensors (e.g. optical sensors). This provides information about the component geometry and the damage size, here serving as input data on part and damage characteristics. In addition, the obtained data are utilized for subsequent simulations of the repair process. From this information, needed requirements for the repair can be derived that then define the setting of the necessary process parameters. These include settings of the primary parameters (CS parameters like process gas temperature, pressure etc.) and secondary parameters (robotic parameters like stand-off distance, transverse velocity etc.). The definition of knowledge-based thresholds for maximum deviation from ideal impact angle and other boundary conditions, should then allow to deduce a suitable repair geometry and conditions for pre-processing for individual component defects. This serves as a starting point for the simulative optimization procedure of the actual repair. Within the fixed framework of part and robot coordinates, the damaged area of the component will be pre-processed by milling. This should ensure removing of possibly damaged material and prepare the needed geometrical conditions for CS with respect to needed impact angles for optimum deposit qualities [23]. Component geometry, defect size and tolerance limits define the working area and the damaged areas to be machined by milling and subsequently repaired by CS.

An essential part of the integrated cell concerns the possible coupling of simulative optimization procedures for the individual component besides the real process. In ideal, fast computation and parameterization in databases should allow to develop an automated process that operates on basis of all key data of the respective component. This concerns assigning of toolpaths for machining as well as the simulation of the toolpath planning for the following deposition. For the selected start-geometry, tools and conditions for milling and possibly other pre-processing can be derived by simulation. The once set repair geometry is also the basis for planning and simulation of the spray toolpath, in ideal running in parallel. The holistic models in the background should combine domains of materials science for CS and automation technology for robotics. This includes the use of individually determined, material dependent parameterization of optimum cold spray parameter sets and respective thresholds for toolpath planning in machining and deposition to achieve the desired design requirements.

The planning of the pre-processing is optimized for meeting all requirements for optimum preparation of surface geometries to safely enable needed spray path and trajectories. The illustrated simulation workflow is designed to determine optimized pre-processing and spray toolpaths at any time by coupling respective adjustments. Calculated conditions according to the simulations are transferred to the real repair system after sufficient convergence within defined boundary conditions. The suggested combination of primary and secondary parameters should enable an overall optimum result to restore the original shape, while ensuring the needed material properties.

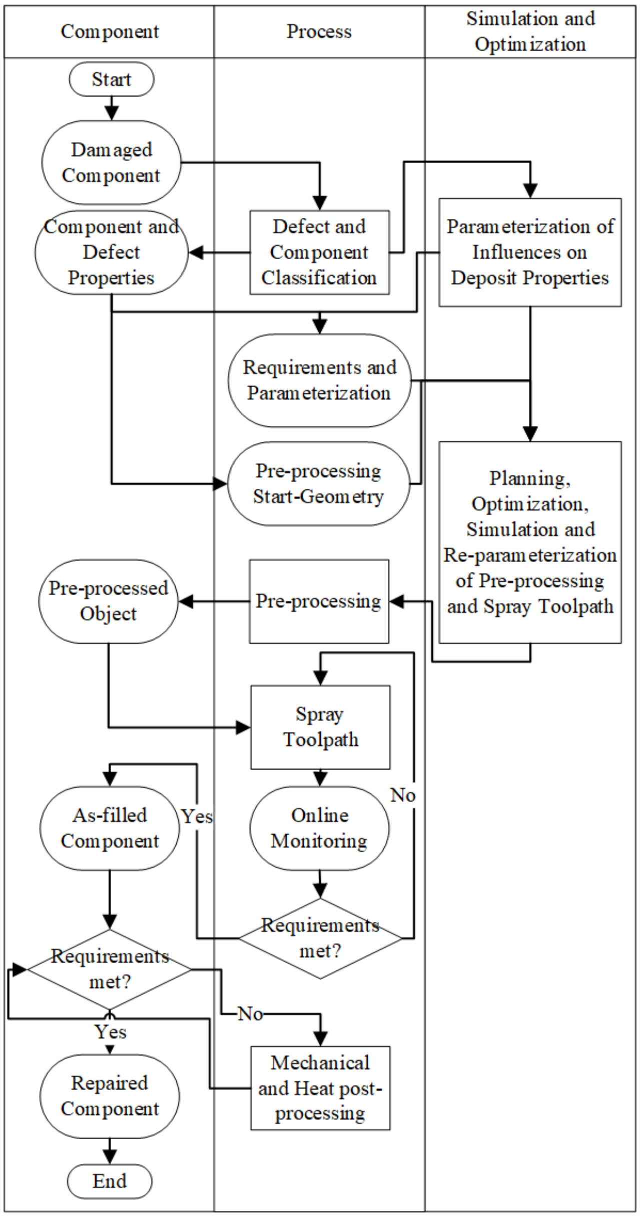


FIGURE 4: FLOW CHART OF THE AUTOMATED COLD SPRAY REPAIR.

In real system performance, disturbances can occur during the spray process. To detect and ideally compensate these disturbances, on-line monitoring can be performed. Here, sensors can be used for on-line control of the built-up layer geometry and quality in comparison to the target values from the simulation. After CS deposition, the as-filled component gets subject to post-processing. This could include further property enhancement, and in any case the final shape adjustment. The application of post treatments and post-machining allows the application of a precisely targeted repair workflow. In order to guarantee the required material properties of the repaired component, non-destructive performance tests must be performed.

IV. Development of Deposit Property Description

A. Deposit Optimization - Primary Influences

In first sets of optimization, Al6061 powder were ordered in different, defined particle size distributions to reveal possible differences in deformation and bonding. The particle strengths were determined by single powder particle compression tests [17].

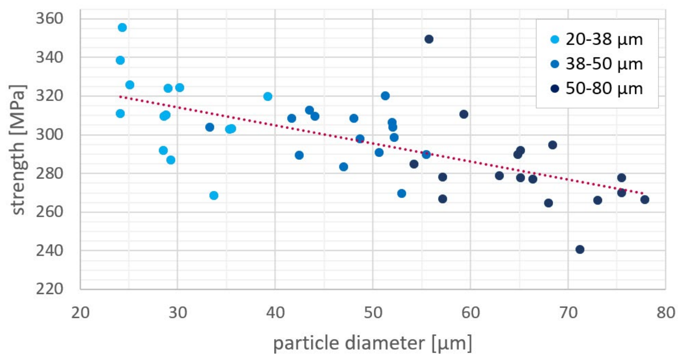


FIGURE 5: STRENGTHS OF AL6061 POWDER PARTICLES OF DIFFERENT SIZE BATCHES IN AS DELIVERED STATES.

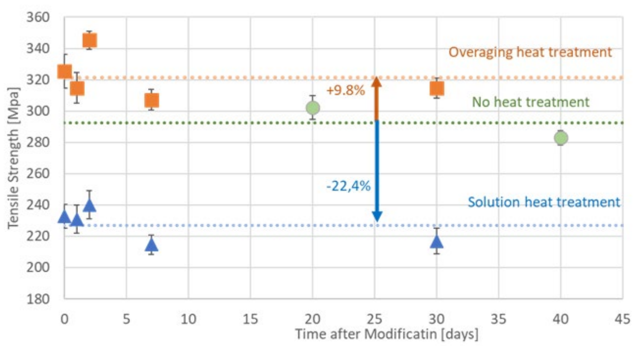
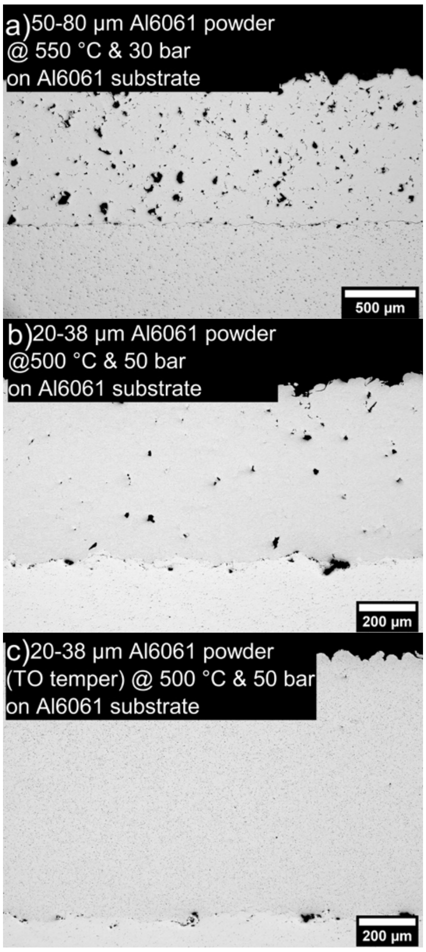


FIGURE 6: DEVELOPMENT OF AL6061 POWDER STRENGTHS AFTER MODIFICATION BY SOFT TEMPER (SOLUTIONIZING, T0) AND OVERAGING OF 38-50µM SIZED AL6061 POWDER.

The data reveal that ultimate powder strengths slightly decrease with size from about 320 to about 260 MPa and are more than twice as high as strengths of soft annealed bulk material. The high powder strength is attributed to fine grained microstructures by rapid solidification in powder production by gas atomization and possibly room temperature aging during storage. In consequence, high critical velocities in cold spraying could restrict attainable deposit properties. As shown in FIGURE 6, powder modification by heat treatments for solutionizing could successfully reduce powder strengths by about 22 %, then not resulting in a strength increase during storage for more than a month.

Comparing the performance in cold spraying under identical conditions, the use of soft annealed instead of as delivered powder could increase the deposition efficiency by about 25 %. Examples for deposit microstructures of Al6061 are shown in FIGURE 7 for using as atomized and soft annealed powders. Applying higher parameter sets for as delivered powder, deposit microstructures could already be significantly improved, reducing the porosity from 3.4 % to about 0.1 %. The use of soft annealed powder at the high spray parameter set results in a rather homogenous deposit microstructures with negligible porosity that in as polished state not allows to reveal any features from particles-particle interfaces. The improvement scales with η ranging from 1,1 to 1,3, and should allow for further optimization. Property analyses of differently prepared deposits are currently under investigation to supply more evidence in respective influences, as well as first sets of experiments with other Al-alloys and Ti as deposit material.



a.

b.

FIGURE 7: DEPOSIT MICROSTRUCTURES AS OBTAINED BY COLD SPRAY OF AS DELIVERED (A, B) AND SOFT ANNEALED POWDERS. COLD SPRAYING WAS PERFORMED WITH PARAMETER SETS OF (A) P_{GAS} = 30 BAR, T_{GAS} = 550°C WITH POWDER SIZED 50-80µM AND (B, C) P_{GAS} = 50 BAR, T_{GAS} = 500°C WITH POWDER SIZED 20-38µM.

B. *Deposit optimization-Secondary influences*

Selected Al6061 deposits were investigated by stress analyses via strain relaxation by hole drilling as well as peak shifts in X-ray diffraction according to the $\sin^2(y)$ correlation. Needed elastic constants for stress calculations were determined by ultrasonic testing. The elastic constants of the deposit are about 5-10 % lower than that of comparable bulk material, which could be attributed to internal defects, most likely non-bonded interfaces. FIGURE 8 shows the example of depth profile of stress distribution for a deposit cold sprayed with the medium size powder (38-50 µm) using a parameter set with p_{gas} = 30 bar, T_{gas} = 500°C.

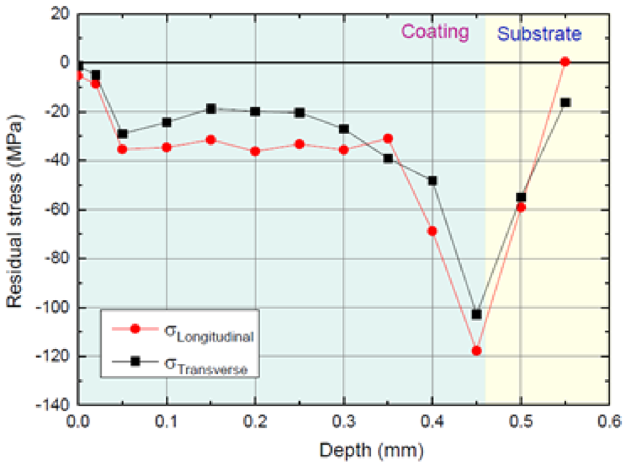


FIGURE 8: DEPTH DISTRIBUTION OF INTRINSIC STRESSES AS OBTAINED BY XRD-ANALYSES OF A AL6061 DEPOSIT, COLD SPRAYED WITH THE MEDIUM SIZE POWDER AT P_{GAS} = 30 BAR, T_{GAS} = 500°C.

Within the deposit, the stresses are rather constant and slightly compressive with about -30 MPa. In contrast, higher compressive stresses of about -120 MPa are obtained at the interface to the substrate, here over a distance of about 100 µm within the substrate then declining to zero. The mainly compressive nature of stresses can be attributed to peening effects under the high velocity particle impact. However, the rather low values within the deposit indicate that other effects might be superimposed. Possible explanations might be given by either i) tensile stresses due to thermal gradients or ii) recrystallization and plastic deformation, or even combinations of both.

Since local stress states could be decisive for repair applications, further investigations are in progress by combining experiments and simulation to distinguish different influences and to derive correlations with spray conditions and used robot kinematics.

For determining the thermal history of a deposit during cold spraying, temperature analyses are coupled with simulation. This combination should allow for calibration of heat flux, means heat input by cold spraying and losses to the environment, as well as heat diffusion over the part. The model setup and a snapshot of temperature distribution for spraying one layer gas only is given in FIGURE 9. The red stripe indicates the high temperatures that are reached within the most upper nozzle scan line out of the set of lines propagating from bottom of the substrate to the top during spraying of one complete layer.

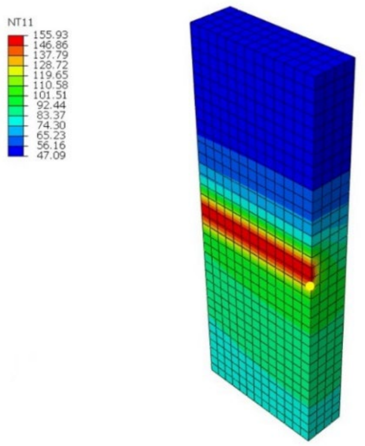


FIGURE 9: SIMULATION MODEL SET-UP AND TEMPERATURE DISTRIBUTION FOR APPLYING ONE LAYER GAS JET IN CS.

FIGURE 10 compares the simulation results of such one layer scan with the experimentally determined surface temperature of a four-layer scan, as measured by a thermocouple, here just applying the cold spray gas jet without powder feeding at p_{gas} = 30 bar, T_{gas} = 500°C. The inserted graph focuses only on the first layer of experimental results and compares the temperature developments with one-layer simulation results. By calibrating the heat flux, the modelled surface temperature could be tuned to experimentally obtained ranges, then allowing to derive more details. The observed surface temperature of more than 100°C in case of Al-alloys should already allow for thermal recrystallization, and thus associated stress relaxation. In next steps, the models should be extended to study possible influences of temperature gradients on internal stress distributions. The results should be used to forecast the thermal history under real process conditions and to define boundary conditions for the most favorable kinetics in robot path generation.

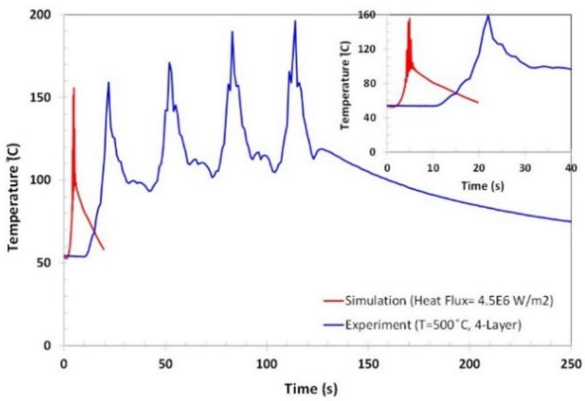


FIGURE 10: COMPARISON OF MODELLING THE SURFACE TEMPERATURE FOR APPLYING ONE-LAYER GAS JET SPRAYING AND THE EXPERIMENTALLY DETERMINED TEMPERATURE FOR FOUR-LAYERS WITH COLD SPRAY PARAMETER SETS OF P_{GAS} = 30 BAR, T_{GAS} = 500°C ONTO AN AL6061 SUBSTRATE IN A STAND-OFF DISTANCE OF 30 MM. THE INSERT COMPARES RESULTS ON TEMPERATURE DEVELOPMENT FROM SIMULATION WITH EXPERIMENTAL ONES DURING THE FIRST LAYER PASS.

C. Single line tracks and 3-D deposits

In cold spraying, the deposit is build-up by the powder distribution in the free jet after passing usually axisymmetric de-laval nozzles. Particle numbers and velocities can be described by peak functions, and thus, in consequence, also the associated material build-up under the spray jet, similar to use of an air-brush. The respective 3-D lines are then assembled to needed 3D-shapes. Solutions of this task are not straight forward and have to consider influences by stand-off distances to the substrate surface and impact angles on single line track shapes. Thus, the development of track shapes has been experimentally investigated and modelled for a range of possible situations that might be given in real processes. FIGURE 11 illustrates the material deposition in single line tracks by an experimental example of a cross section through an Al6061 deposit line orthogonally cold sprayed and the modelled deposit distribution under the spray jet. The comparison shows that peaks functions can be used to describe deposition. FIGURE 12 summarizes the profile shapes and skewness as obtained by using different spray angles. The increasing deviation in symmetry with decreasing spray angle is used for calibrating peak functions. Similar has was done for using different stand distances to the substrate (not shown here). The above description has been developed into a model for shape build-up including the main parameters for cold spraying. First results are shown in FIGURE 13, here demonstrating how line distance could influence surface pattern. This already indicates how line distances and impact angle influence the deposit shape and topography. Next refinements of the model concern the angular situation due to already build-up spray layers and influences on skewness and local deposition efficiency.

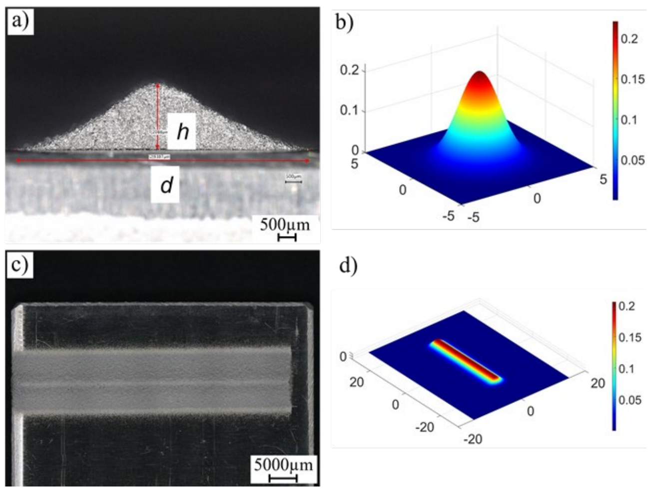


FIGURE 11: MATERIAL DEPOSITION IN SINGLE LINE TRACKS. A) CROSS SECTION THROUGH A AL6061 DEPOSIT LINE ORTHOGONALLY COLD SPRAYED WITH P_{GAS} = 30 BAR, T_{GAS} = 500°C ONTO A ALMG3 SUBSTRATE IN A STAND-OFF DISTANCE OF 30 MM, B) MODELLED DEPOSIT DISTRIBUTION UNDER THE SPRAY JET, C) DEPOSIT DISTRIBUTION IN THE SINGLE LINE AS DETERMINED BY MICROCOPY AND D) MODELLED SINGLE LINE TRACK UNDER THE SPRAY JET

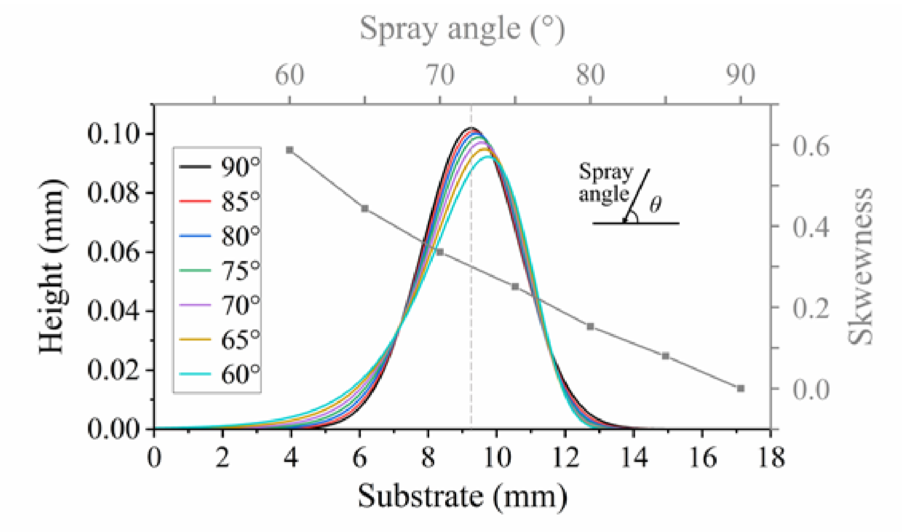


FIGURE 12: PROFILES SHAPES AND SKEWNESS OF SINGLE LINE TRACKS AT DIFFERENT SPRAY ANGLES.

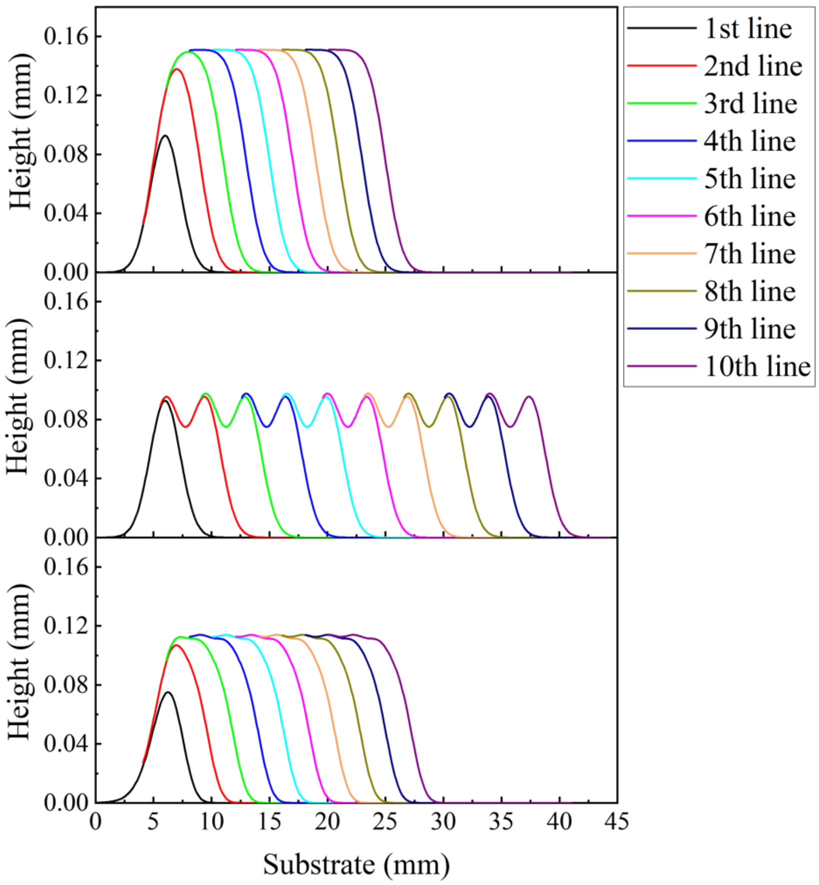


FIGURE 13: MODEL RESULTS FOR ASSEMBLING SPRAY LINES TO A DEPOSIT FOR REPAIR IN COLD SPRAY, WITH A) LINE DISTANCE OF 2 MM AND SPRAY ANGLE OF 90°, B) LINE DISTANCE OF 3.5 MM AND SPRAY ANGLE OF 90°, C) LINE DISTANCE OF 2 MM AND SPRAY ANGLE OF 75°.

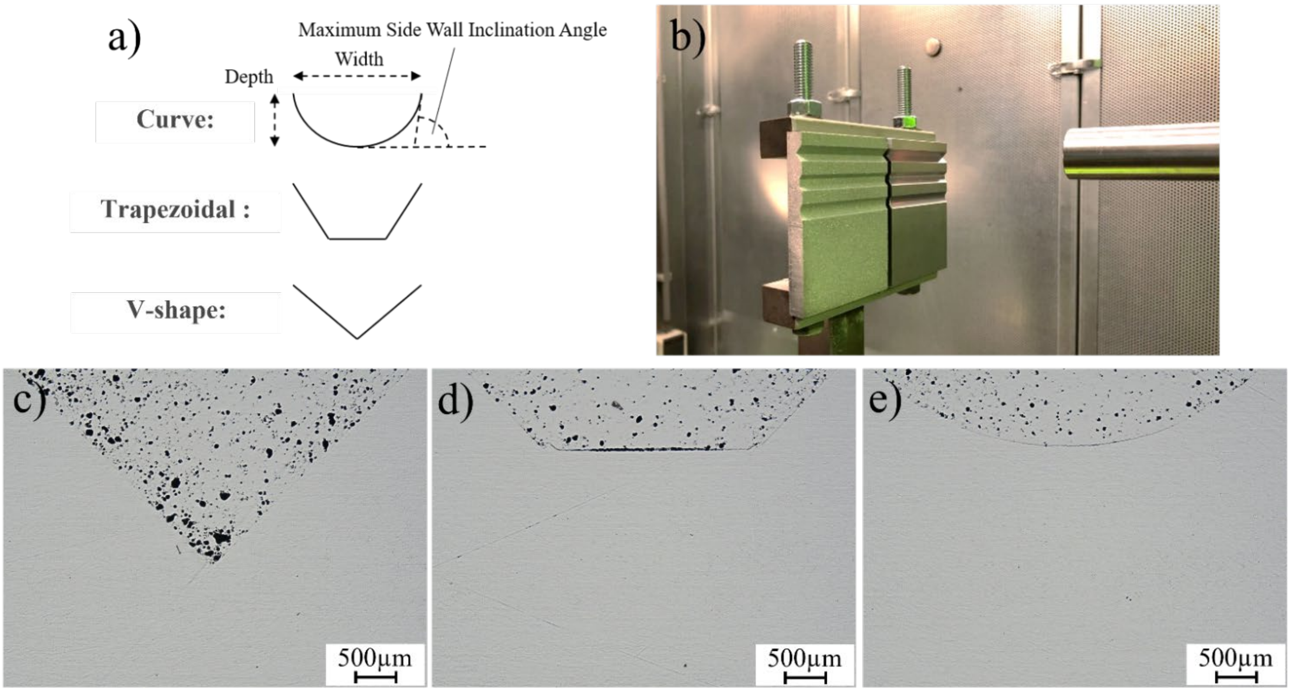


FIGURE 14: EXAMPLES FOR FILLING OF CAVITIES WITH A) SCHEMATIC OF DIFFERENT GROOVE GEOMETRIES, B) THE EXPERIMENTAL SET-UP AND C), D) E) EXAMPLES OF DEPOSIT MICROSTRUCTURES WITHIN FILLED CAVITIES.

D. Filling of Cavities

Success of by cold spray deposition and associated deposit qualities depends on local impact angles. In filling of cavities, the situation gets more difficult by particle deceleration under more pronounced bow-shock effects. As case study for cavity filling, several artificial groove types were prepared and filled by cold spraying by an orthogonal pass. Dimensions, set-up and examples of deposits are given in FIGURE 14. The deposit microstructures, in detail porosities confirm the manifold influence of cavity shapes on deposit qualities. Particularly layer build-up onto sharp edges and shape transitions seems to cause problems. Despite similar side angles, the microstructures with the cavity with a flat base shows less porosity at the side than the one with the sharp groove. However, the flat base suffers from problems with adhesion. In contrast, the microstructure within the smooth cavity is showing a rather homogenous porosity and overall a uniform interface appearance to the base material. More investigations are on the way to describe boundary conditions for general cavity shapes, tolerable deposit angles and transitions in shape.

E. Toolpath programming

The successful restoration of a specified damaged part to the needed shape and size by cold spraying requires the implementation of an accurate toolpath, which is also essential to meet the basic performance requirements. The planning, programming and subsequent implementation of the paths need to consider the various boundary conditions of the deposition, robot kinematics and the physical environment and layout. For each segment of the damage area, a high precision of spray path tracks and applied parameters is needed. Apart from spray angle, stand-off distance, as well as scanning speed and scanning step width, issues related to local heating and possible thermal stresses also should be considered. FIGURE 15 shows an example of cold spray toolpath planning, programming and implementation using robotic offline programming technology. This method enables the set toolpath to be exactly applied to each spraying target point. Process simulation in a virtual workstation allows for robot kinematics analysis, toolpath optimization and physical collision detection. As a result, the calibrated robot program is transferred to the real robot controller for execution. Future work will further investigate more strategies and analysis for robot trajectory planning and optimization in complex geometry reconstruction to achieve the expected cold-spray material deposition and desired repair quality.

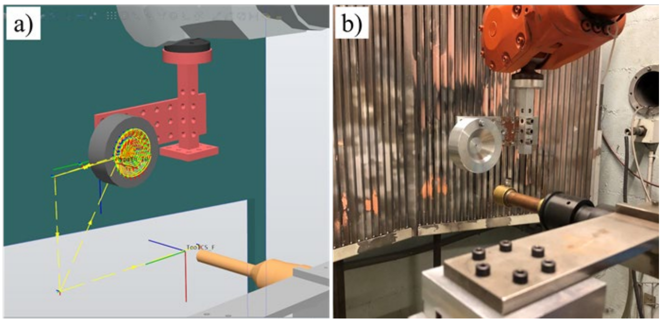


FIGURE 15: A) TOOLPATH SIMULATION IN THE VIRTUAL WORKSTATION, AND B) PROCESS IN A REAL SPRAY ENVIRONMENT.

V. SUMMARY AND CONCLUSIONS

To provide sophisticated repair solutions for aerospace applications, the suggested concept uses an interdisciplinary approach ranging from basic materials science of CS deposition by experiments and modelling to computer supported automation technologies and practical engineering applications. Within the limited frame of this project overview, only some snapshots and selected results of the different subtopics could be presented. So far, the results within the different topics already demonstrate the variety of influences on deposit qualities for possible repair and provide first correlations for the holistic concept of a general, digital description.

In order to successfully transfer the entire framework, methods and results to the real part repair applications in the future, further work is under progress for optimizing CS deposition techniques and thus deposit properties. Linking approaches of fluid mechanics, pre- and post-processing as well as non-destructive testing into the sketched framework aims for an integrated, digital concept. This concept does not only allow implementation as repair process under enhanced process and quality control. Apart from that, the suggested strategies can furthermore provide a more advanced theoretical basis for cold spray additive manufacturing in general, and for easy transfer to other engineering applications.

ACKNOLODGEMENT

Funding by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr is greatly acknowledged [project CORE].

REFERENCES

[1] T. Vandermaesen, R. Humphries, M. Wackernagel, A. Murthy, and L. Mailhes, "EU Overshoot Day Living beyond Nature's Limits. 10 May 2019," *WWF. Available online: https://www.footprintnetwork.org/content/uploads/2019/05/WWF-GFN-EU-Overshoot-Day-report.pdf (accessed on 29 August 2022)*.

[2] W. McDonough and M. Braungart, *Cradle to cradle: Remaking the way we make things*: North point press, 2010.

[3] K. R. Ernst *et al.,* "Anwendungsvielfalt des Kaltgasspritzens / Diversity of Applications for Cold Spraying," in *Proceedings of 9. Kolloqium Hochgeschwindigkeits-Flammspritzen*, Erding, Germany, 2012, pp. 159–170.

[4] S. Ford, M. Despeisse, and A. Viljakainen, "Extending product life through additive manufacturing: the sustainability implications," in *Global Cleaner Production and Consumption Conference, Sitges, Barcelona, Spain*, 2015, pp. 1–4.

[5] A. Saboori, A. Aversa, G. Marchese, S. Biamino, M. Lombardi, and P. Fino, "Application of Directed Energy Deposition-Based Additive Manufacturing in Repair," *Applied Sciences*, vol. 9, no. 16, p. 3316, 2019, doi: 10.3390/app9163316.

[6] R. French, M. Benakis, and H. Marin-Reyes, "Process monitoring and industrial informatics for online optimization of Welding Procedure Specifications (WPS) in Gas Tungsten Arc Welding (GTAW) – Industry 4.0 for robotic additive remanufacturing of aeroengine components," in *2018 3rd International Conference on Advanced Robotics and Mechatronics (ICARM)*, Singapore, 72018, pp. 812–817.

[7] M. E. Lynch *et al.,* "Design and topology/shape structural optimisation for additively manufactured cold sprayed components," *Virtual and Physical Prototyping*, vol. 8, no. 3, pp. 213–231, 2013, doi: 10.1080/17452759.2013.837629.

[8] C. M. Kay and J. Karthikeyan, Eds., *High Pressure Cold Spray: Principles and Applications*. Materials Park OH: ASM International, 2016.

[9] H. Assadi, H. Kreye, F. Gärtner, and T. Klassen, "Cold spraying – A materials perspective," *Acta Materialia*, vol. 116, pp. 382–407, 2016, doi: 10.1016/j.actamat.2016.06.034.

[10] P. Cavaliere and A. Silvello, "Crack Repair in Aerospace Aluminum Alloy Panels by Cold Spray," *J Therm Spray Tech*, vol. 26, no. 4, pp. 661–670, 2017, doi: 10.1007/s11666-017-0534-9.

[11] K. Binder, J. Gottschalk, M. Kollenda, F. Gärtner, and T. Klassen, "Influence of Impact Angle and Gas Temperature on Mechanical Properties of Titanium Cold Spray Deposits," *J. Therm. Spray Tech.*, vol. 20, 1-2, pp. 234–242, 2011, doi: 10.1007/s11666-010-9557-1.

[12] P. Leyman and V. K. Champagne, "Cold Spray Process Development for the Reclamation of the Apache Helicopter Mast Support," ARMY RESEARCH LAB ABERDEEN PROVING GROUND MD WEAPONS AND MATERIALS RESEARCH DIRECTORATE, 2009.

[13] C. A. Widener *et al.,* "Application of High-Pressure Cold Spray for an Internal Bore Repair of a Navy Valve Actuator," *J Therm Spray Tech*, vol. 25, 1-2, pp. 193–201, 2016, doi: 10.1007/s11666-015-0366-4.

[14] H. Wu, S. Liu, X. Xie, Y. Zhang, H. Liao, and S. Deng, "A framework for a knowledge based cold spray repairing system," *J. Intell. Manuf.*, pp. 1–9, 2021, doi: 10.1007/s10845-021-01770-7.

[15] H. Assadi *et al.,* "On Parameter Selection in Cold Spraying," *J Therm Spray Tech*, vol. 20, no. 6, pp. 1161–1176, 2011, doi: 10.1007/s11666-011-9662-9.

[16] W. Wong, P. Vo, E. Irissou, A. N. Ryabinin, J.-G. Legoux, and S. Yue, "Effect of Particle Morphology and Size Distribution on Cold-Sprayed Pure Titanium Coatings," *J Therm Spray Tech*, vol. 22, no. 7, pp. 1140–1153, 2013, doi: 10.1007/s11666-013-9951-6.

[17] H. Assadi and F. Gärtner, "Particle Compression Test: A Key Step towards Tailoring of Feedstock Powder for Cold Spraying," *Coatings*, vol. 10, no. 5, p. 458, 2020, doi: 10.3390/coatings10050458.

[18] S. Theimer, M. Graunitz, M. Schulze, F. Gaertner, and T. Klassen, "Optimization Adhesion in Cold Spraying onto Hard Substrates: A Case Study for Brass Coatings," *J Therm Spray Tech*, vol. 28, 1-2, pp. 124–134, 2019, doi: 10.1007/s11666-018-0821-0.

[19] K.-R. Ernst, J. Braeutigam, F. Gaertner, and T. Klassen, "Effect of Substrate Temperature on Cold-Gas-Sprayed Coatings on Ceramic Substrates," *J Therm Spray Tech*, vol. 22, 2-3, pp. 422–432, 2013, doi: 10.1007/s11666-012-9871-x.

[20] S. Yin, X. Suo, Y. Xie, W. Li, R. Lupoi, and H. Liao, "Effect of substrate temperature on interfacial bonding for cold spray of Ni onto Cu," *J Mater Sci*, vol. 50, no. 22, pp. 7448–7457, 2015, doi: 10.1007/s10853-015-9304-6.

[21] Z. Arabgol, H. Assadi, T. Schmidt, F. Gärtner, and T. Klassen, "Analysis of Thermal History and Residual Stress in Cold-Sprayed Coatings," *J Therm Spray Tech*, vol. 23, 1-2, pp. 84–90, 2014, doi: 10.1007/s11666-013-9976-x.

[22] M. Lewke, S. Nielsen, A. List, F. Gartner, T. Klassen, and A. Fay, "Knowledge-based Optimization of Cold

Spray for Aircraft Component Repair," in *2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Vasteras, Sweden, 2021, pp. 1–4.

[23] S. Yin *et al.,* "Cold spray additive manufacturing and repair: Fundamentals and applications," *Additive Manufacturing*, vol. 21, pp. 628–650, 2018, doi: 10.1016/j.addma.2018.04.017.

Islanded operation of an inverter dominated coupled multi-energy system

Edgar Diego Gomez Anccas*, Johannes Blanz, Detlef Schulz
Helmut-Schmidt-University / University of the Federal Armed Forces Hamburg
Professorship of Electrical Power Systems
*diego.gomez@hsu-hh.de

***Abstract* – The transition from fossil energy to renewables creates challenges concerning grid resilience due to the volatility of power generation based on solar and wind energy and the loss of inertia from synchronous machines. To tackle the temporal and spatial discrepancies between generation and consumption of renewables additional energy storage is necessary. A promising solution is the coupling of different energy sectors, especially gas and electricity, in order to support the sensitive electric grid through gas-to-power technologies such as fuel cells and the possibility to store surplus of electrical energy using power-to-gas technologies such as electrolysers. Even though research on these technologies is steadily advancing the dynamic interactions in strongly coupled systems is not fully understood. This work focuses on islanded microgrids consisting of a hydrogen and electric system coupled through a fuel cell system that is used to set up grid voltage and frequency. The system is simulated in order to test its functionality as grid forming unit during dynamic load changes and volatile power injection via a PV system.**

***Keyword* – Multi-energy-system, inverter-dominated island grid, sector coupling, grid-forming fuel cell operation**

NOMENCLATURE

FC	Fuel cell
H_2	Hydrogen
LV	Low voltage
GtP	Gas-to-Power
MPPT	Maximum-Power-Point-Tracking
PtG	Power-to-Gas
PV	Photovoltaic
REDIBEL	Reversibel-Digital-gekoppelte-Brennstoffzelle-und-Elektrolyse (Engl. Reversible-Digitally-coupled-Fuel Cell-and-Electrolyser)
SM	Synchronous Machine

I. INTRODUCTION

Decarbonization of the existing electrical energy system leads to an increasing share of volatile renewables in the energy mix. To ensure grid stability and reliability of supply under these conditions the whole field of energy storage will have to play a more prominent role [1]. In addition to the temporal volatility of renewable energy sources, their efficiency depends on their geographical location [2, 3]. A promising solution to the temporal and spatial challenges of modern energy grids is the coupling of the energy sectors to multi-energy systems [4]. This is realized using an electrical grid, fed by different energy sources, e.g., electron- and gas-based energy carriers, which are coupled with technologically suitable conversion technologies. The possibility to redistribute energy amongst and share energy storage capabilities across different sectors leads to increased flexibility in all the energy sectors coupled in the here proposed fashion [5]. Political incentives in the context of the *Nationale Wasserstoffstrategie* (Climate Action Programme putting hydrogen centre stage to achieve an energy mix consisting of 100 % renewables) in Germany encourages the use of hydrogen (H_2) as a key energy carrier in future energy systems [6]. Bidirectional energy flow between gas and electric sectors can be achieved using coupling technologies for Power-to-Gas (PtG) and Gas-to-Power (GtP) operations such as electrolysers and fuel cells (FC), respectively. However, due to different dynamic properties of those two technologies and the requirement of power electronics to connect the DC-based coupling technologies to the electric system intelligent control mechanisms are necessary [7].

The research project CoupleIT! aims to create a laboratory and simulation environment in order to investigate dynamic interactions between electric and H_2 systems coupled by a REDIBEL (Reversible-Digitally-coupled-Fuel Cell-and-Electrolyser)-system. The planned microgrid is depicted in FIGURE 1. The research is focused on the behaviour under the rough conditions of islanding operation with volatile PV supply and dynamic load changes. In this work a low voltage AC-microgrid consisting of a FC-system in parallel to a PV system and an AC-load is operated in islanded mode in a simulation environment. In section II of this paper the necessary control methods in order to operate the microgrid in islanded operation are presented. Section III presents the models used in the simulation followed by section IV elaborating on the test cases and simulation results. Finally, the conclusion summarises the results and the outlook offers a glance into the project's future.

https://doi.org/10.24405/14525

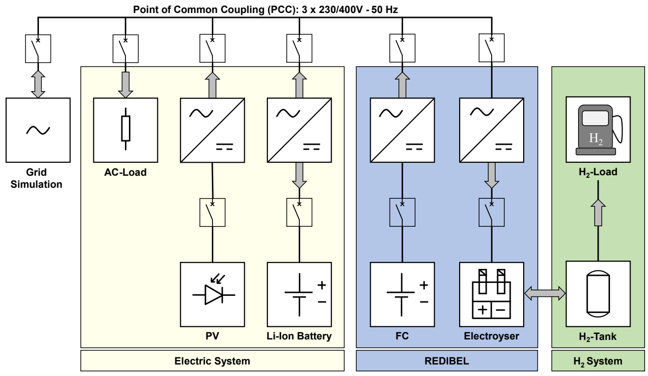


FIGURE 1: MULTI-ENERGY-MICROGRID CONSISTING OF TWO ISLANDED ENERGY SYSTEMS COUPLED BY THE REDIBEL-SYSTEM.

II. METHODS

A. Grid-Feeding Control – PV

Grid-feeding control operates converters by defining values for active and reactive power that is injected to the grid. Additionally, these converters can contribute to the voltage and frequency control in AC-microgrids [8]. PV sources are usually run using grid-feeding control. However, instead of using active and reactive power setpoints a Maximum-Power-Point-Tracking (MPPT)-algorithm is used to yield the maximum output of a PV system. The AC-grid connection is realised via a boost stage and an inverter. The boost stage serves as the PV-side control stage that maximizes the power output of the source. The grid-side control of the inverter balances the DC-link voltage in order to maintain a power equilibrium between PV- and grid-side and preserve the power quality by controlling the supplied grid current [9]. A typical control cascade of a grid-feeding PV-inverter is depicted in FIGURE 2, where v_{dc}^* and v_{dc} are the reference and measured DC-link voltages, respectively, i_{dq}^* and i_{dq} are the reference and output currents, respectively, and v_{dq}^* is the switching node output reference voltage in *dq*-coordinates. Grid-feeding control operates power converters as current sources that require a synchronisation stage to an existing grid. Therefore, grid-feeding converters are reliant on grid-forming, grid-supporting or synchronous machines (SM) to set up both voltage amplitude and frequency [10].

B. Grid-Forming Control – FC

Grids dominated by SMs benefit from the inherent voltage forming and inertial behaviour of the machines. The ability to smoothen frequency deviations utilitsing the kinetic energy stored in the rotor of SMs is to be emulated in some way in future inverter dominated grids lacking said machines. The grid connection of renewable sources needs power electronics with tailored control algorithms in order to emulate the voltage forming and inertial behavior of synchronous machines.

These inverters are called grid-forming inverters. A grid-forming control method that exploits the similarity between a converter and an SM model is called "matching control" [11]. It exploits the important characteristic of the DC bus voltage to reflect power imbalances in a system and uses these as a feedback reference signal.

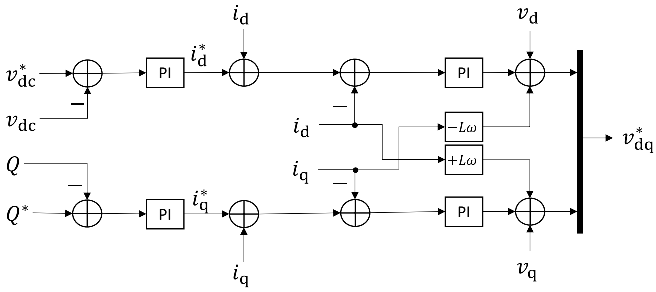


FIGURE 2: GRID-SIDE CONTROL CASCADE OF A GRID-FEEDING PV-INVERTER.

The grid characteristics are set up using a sinusoidal modulation scheme for the AC-voltage reference in *αβ*-coordinates

$$\hat{v}_{\alpha\beta} = \mu \begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix} \tag{1}$$

with μ and θ as the modulation signal magnitude and angle, respectively. The AC voltage magnitude is controlled using a PI controller

$$\mu = k_{\mathrm{p}}\left(v^* - \|v_{\mathrm{dq}}\|\right) + k_{\mathrm{i}} \int_0^t \left(v^* - \|v_{\mathrm{dq}}(\tau)\|\right) \mathrm{d}\tau \tag{2}$$

with v_{dq} as the measured AC voltage in *dq*-coordinates. The angular dynamics are derived from the commonalities between converter and SM model in the form of

$$\dot{\theta} = \omega = k_{\theta} v_{\mathrm{dc}} \tag{3}$$

using $k_{\theta} \coloneqq w_0 / v_{\mathrm{dc}}^*$ and transforming $\hat{v}_{\alpha\beta}$ to *dq*-coordinates allows the conventional current and voltage cascades being used in control

$$\dot{x}_{\mathrm{vdq}} = \begin{bmatrix} \hat{v}_{\mathrm{d}} - v_{\mathrm{d}} \\ \hat{v}_{\mathrm{q}} - v_{\mathrm{q}} \end{bmatrix} \tag{4}$$

$$i_{sdq}^* = \begin{bmatrix} i_{\mathrm{d}} \\ i_{\mathrm{q}} \end{bmatrix} + C\omega \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} v_{\mathrm{d}} \\ v_{\mathrm{q}} \end{bmatrix} + k_{\mathrm{pv}} \dot{x}_{\mathrm{vdq}} + k_{\mathrm{iv}} x_{\mathrm{vdq}} \tag{5}$$

Where i_{sdq}^*, i_{dq}, $\hat{v}_{\mathrm{dq}}$ and v_{dq} denote switching node reference current, output current, ac voltage reference and measurement ac voltage, respectively, in *dq*-coordinates. The proportional and integral gain are denoted by k_{pv} and k_{iv}, respectively. Using i_{dq}^* the current loop can be derived as

$$\dot{x}_{\mathrm{idq}} = \begin{bmatrix} i_{\mathrm{sd}}^* - i_{\mathrm{sd}} \\ i_{\mathrm{sq}}^* - i_{\mathrm{sq}} \end{bmatrix} \tag{6}$$

$$v_{\mathrm{sdq}}^* = \begin{bmatrix} v_{\mathrm{d}} \\ v_{\mathrm{q}} \end{bmatrix} + L\omega \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + k_{\mathrm{pi}} \dot{x}_{\mathrm{idq}} + k_{\mathrm{ii}} x_{\mathrm{idq}} \tag{7}$$

where v_{sdq}^*, $i_{\mathrm{sdq}} = \left[i_{\mathrm{sd}}, i_{sq}\right]^{\top}$, k_{pi} and k_{ii} are reference switching node voltage, switching node current, proportional and integral gains, respectively.

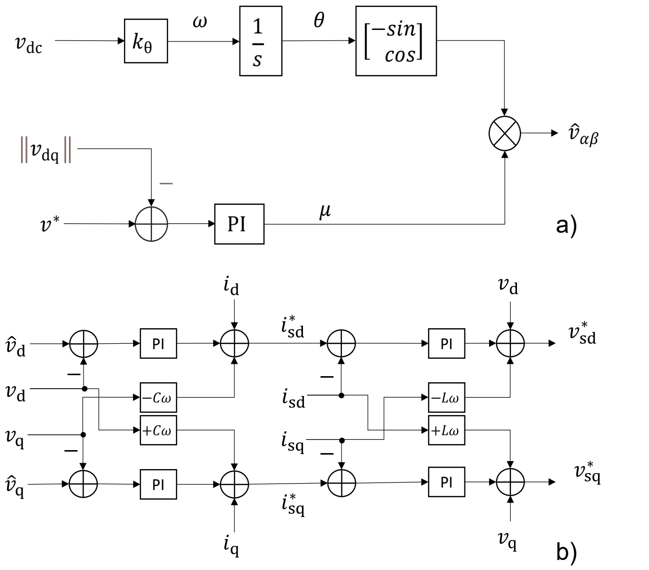


FIGURE 3: BLOCK DIAGRAMS OF THE MATCHING CONTROL A) AND THE CASCADED CONTROL DESIGN B) OF THE INVERTER.

An FC-system can be used as a grid-forming source owing to its reliable and controllable output that is only dependent on the supply of reactants. However, dynamic operation adversely affects an FC's longevity. For this reason, a supporting element is necessary to smooth steep output gradients [12].

C. Grid Simulations

The simulation environment for the coupled energy systems is MATLAB/Simulink® as well as the SimPowerSystems and Thermolib Toolboxes for power systems and thermodynamic simulations, respectively [13].

III. MODELS

The investigated model consists of an FC system run as grid-forming unit using the controller aspects described in II.B to set up a low voltage (LV) 230/400 V, 50 Hz AC-microgrid. The FC system is connected in parallel to a PV system operated in grid-feeding mode according to section II.A. The two sources feed an AC load.

A. FC-Model

The FC-model includes an anode, a cathode, a heat transfer and an energy calculation system. The voltage of a single cell is defined by the following equation:

$$v_{\mathrm{fc}} = E - v_{\mathrm{act}} - v_{\mathrm{ohm}} - v_{\mathrm{conc}} \tag{8}$$

where E is the Nernst voltage, v_{act} the activation losses, v_{ohm} the ohmic losses and v_{conc} the concentration losses [14]. The Nernst voltage is a function of temperature and oxygen and as well as H_2 partial pressures [15]. The activation losses correspond to the energy required to move electrons and break and form chemical bonds and depends on the partial pressure of oxygen and the temperature of the cell [16]. The ohmic losses correspond to the losses that result from the migration of protons through the membrane and movement of electrons through the electrode and are strongly dependent on temperature and membrane humidity [17, 18]. The concentration losses depend, firstly, on the maximum current density that causes precipitous voltage drops and, secondly, on the actual FC current. The fitting parameters are chosen according to [14, 19, 20]. Under the assumption, that all cells in a stack are identical the stack voltage is calculated by scaling up the single cell voltage by the number of cells n according to

$$v_{\mathrm{st}} = n \cdot v_{\mathrm{fc}}. \tag{9}$$

The stack polarization curve and P/I plot are depicted in FIGURE 4. In this model an ideal supply of H_2, air and coolant is assumed. The link between necessary reactant supply for FC operation is calculated according to [21].

$$\dot{n}_{\mathrm{H_2}} = \frac{I \cdot n}{2 \cdot F} \tag{10.1}$$

$$\dot{n}_{O_2} = 2 \cdot \dot{n}_{\mathrm{H_2}} \tag{10.2}$$

Where $\dot{n}$ is the molar flow of H_2/oxygen per second, I the FC current, n the number of cells and F the Faraday constant. The FC system is connected to a DC/DC stage boosting the FC voltage to the desired v_{dc} and a DC/AC stage that is operated as described in section II.B. The model parameters are summarised in TABLE 1.

B. PV – Model

For the simulation of the PV System the SimPowerSystem PV-Array model is used. The array is structured in five parallel strings each containing 10 modules in series. Each module consists of 60 Cells. The U/I characteristics of a module is derived from the 1 Diode equivalent circuit. The circuit dynamics are described by the following equation.

$$I = I_0 \left(e^{\frac{U}{U_T}} - 1 \right) \tag{11}$$

Where I is the module current, I_0 the saturation current, U the module voltage and U_T the thermal voltage [22]. The PV array is connected to the microgrid through a DC/DC and DC/AC stage. The control described in II.A is used to operate the two stages. A constant temperature of 25 °C and a solar power inflow of 250 to 300 W/m^2 is set. The model data for the PV-array is given in TABLE 2.

TABLE 1: FC MODEL PARAMETER.

Air supply pressure	2 bar
H_2 supply pressure	2 bar
Stack temperature	60° C
Nominal power	6 kW
Number of cells	96
Cell area	165 cm^2

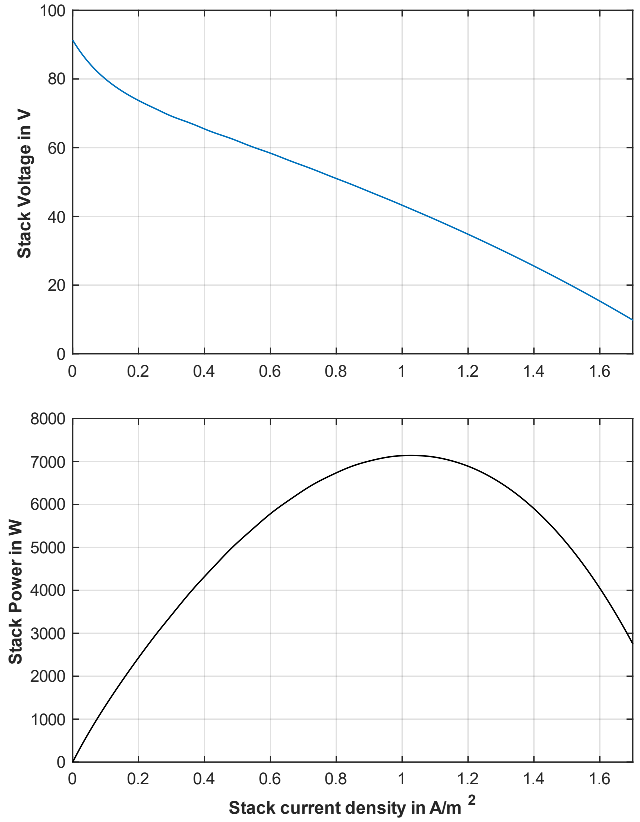


FIGURE 4: POLARIZATION CURVE AND P/I PLOT OF THE STACK

IV. Simulations

A. Grid-forming Fuel Cell System

The stand-alone grid-forming controlled FC-system feeds a static 3 kW AC-load. The examined fault is a load step ΔP of 1 kW during steady state at $t_{step} = 5$ s. In FIGURE 5 a load increase creates a power imbalance that cannot be compensated by the fuel cell alone (FIGURE 5 a)) and is supplemented by discharging the DC-capacitor and thus decreasing v_{dc} (FIGURE 5 b)). As the grid frequency is derived from v_{dc} a load increase induces an increase in grid frequency, resulting in the desired behaviour of a grid-forming unit (FIGURE 5 c)). In FIGURE 5 d) the power equilibrium between injected active power and load is shown. The matching control of the fuel cell system is able to track the desired load power. However, due to the DC-side control focus on keeping v_{dc} at 700 V and not taking losses into account an offset between P_{Load} and P_{FC} occurs.

TABLE 2: PV MODEL PARAMETER

Parallel strings	5
Modules per string	10
Cells per module	60
Module open circuit voltage	36.3 V
Module short circuit current	7.84 A
Saturation current	2.9273 x 10^{-10} A
Diode ideality factor	0.98119

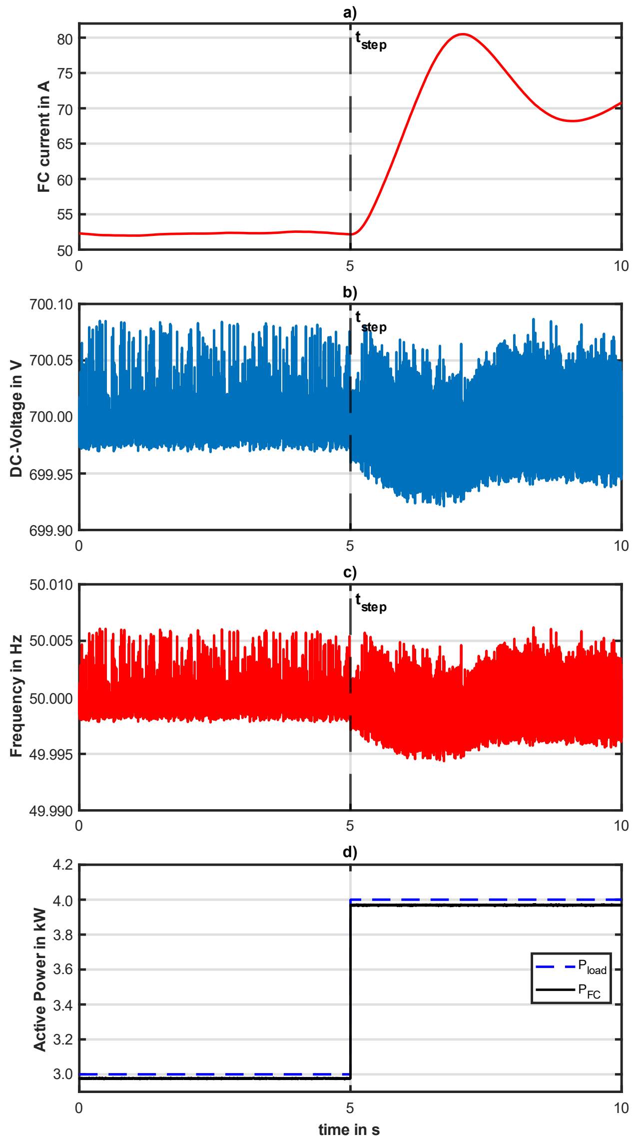


FIGURE 5: RESPONSE OF FC CURRENT a), DC VOLTAGE b), MICROGRID FREQUENCY c), AND ACTIVE POWER d) DURING A LOAD EVENT AT $t_{STEP} = 5$ s.

B. Fuel Cell in parallel to PV during load variation

In the previous section the transient behavior of the grid-forming FC-system during a load step was examined. Now, the long-term behavior of the system during dynamic load changes and variable power injection needs to be investigated. In this section the grid-forming FC System is run in parallel to the PV system described in section III.B. The sources feed an AC-load of 5 kW during 5 hours. The static load pulses by a ΔP of 1 kW every 30 minutes. In FIGURE 6 the system's behaviour can be seen. The load pulsation induces a change in v_{dc} at every pulse event (FIGURE 6 a)). As the PV system is operated in grid-feeding MPPT-mode according to II.A it feeds a defined amount of active power into the grid that depends on temperature and solar irradiance. The temperature is fixed at 25 °C and the irradiance is set to cycle between 250 and 300 W/m². In order to meet the experienced load demand, the missing amount is supplied by the FC system (FIGURE 6 b)).

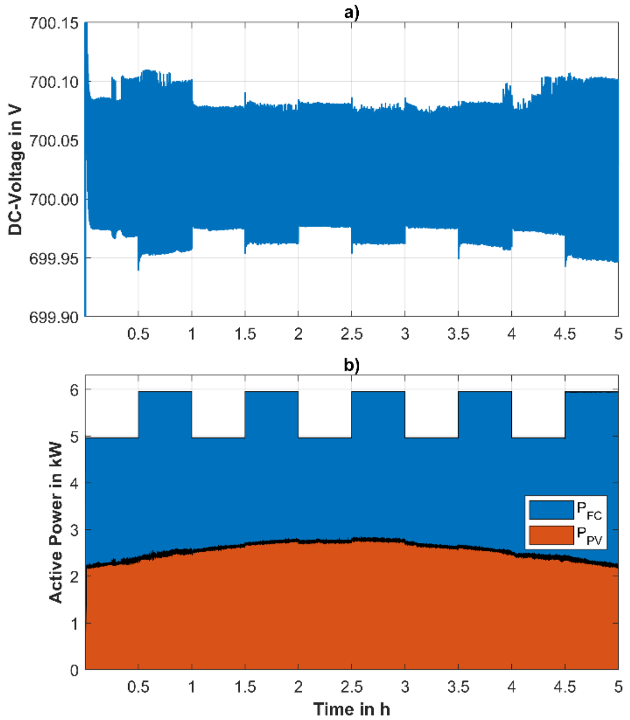


FIGURE 6: DC-LINK VOLTAGE a) AND ACTIVE POWER SUPPLY OF PV (P_{PV}) and FC (P_{FC}) IN b) DURING LOAD PULSES AND VOLATILE POWER INJECTION.

V. Conclusion and Outlook

The aim of the project is to understand the dynamics in a coupled LV AC- and H_2-microgrid in islanded operation. The approach opted for in this work is to employ an FC system as a grid-forming unit as the coupling technology of choice. The matching control technique is selected to operate the grid-forming converter control using a DC reference to derive grid characteristics. The simulation results show that, a stand-alone FC system is able to stabilize the microgrid under transient load events. However, an offset between power injection and consumption is observed due to losses that, as of now, have not been taken into account. Furthermore, a parallel FC and PV system was investigated over an observation period of 5 h. As a result, the grid-forming behavior of the FC system could be validated during volatile energy injection and consumption. Although the results in the simulation environment show that using an FC system with suitable control stabilizes the grid in a power mismatch during short- and long-term events, possible damage to the FC system during load cycling is neglected albeit expected. Additionally, the FC model needs to be extended to include real reactant supply. Thus, future research in the project CoupleIT! will comprise validation of simulation results in a laboratory environment and the inclusion of additional grid-supporting components to reduce the impact of load cycling on the grid forming unit in order to conserve its lifetime.

Acknowledgement

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [Project IT-gestützte Sektorenkopplung: Digital gesteuerte Brennstoff-zellen- und Elektrolysetechnologie für stationäre und mobile Anwendungen – CoupleIT!].

VI. References

[1] M. D. Leonard, E. E. Michaelides, and D. N. Michaelides, “Energy storage needs for the substitution of fossil fuel power plants with renewables,” *Renewable Energy*, vol. 145, pp. 951–962, 2020, doi: 10.1016/j.renene.2019.06.066.

[2] J. Drücke *et al.,* “Climatological analysis of solar and wind energy in Germany using the Grosswetterlagen classification,” *Renewable Energy*, vol. 164, pp. 1254–1266, 2021, doi: 10.1016/j.renene.2020.10.102.

[3] F. Masurowski, M. Drechsler, and K. Frank, “A spatially explicit assessment of the wind energy potential in response to an increased distance between wind turbines and settlements in Germany,” *Energy Policy*, vol. 97, pp. 343–350, 2016, doi: 10.1016/j.enpol.2016.07.021.

[4] M. Wietschel, P. Plötz, B. Pfluger, and M. Klobasa, *Sektorkopplung: Definition, Chancen und Herausforderungen.* [Online]. Available (1st September 2022): http://hdl.handle.net/10419/175374

[5] G. Fridgen, R. Keller, M.-F. Körner, and M. Schöpf, “A holistic view on sector coupling,” *Energy Policy*, vol. 147, p. 111913, 2020, doi: 10.1016/j.enpol.2020.111913.

[6] Bundesministerium für Wirtschaft und Energie (BMWi), *Die Nationale Wasserstoffstrategie*. [Online]. Available (1st September 2022): https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v=20

[7] Bundesamt für Sicherheit in der Informationstechnik, *Standardisierungsstrategie zur sektorübergreifenden Digitalisierung nach dem Gesetz zur Digitalisierung der Energiewende.* [Online]. Available (1st September 2022): https://www.bmwi.de/Redaktion/DE/Downloads/S-T/standardisierungsstrategie.pdf?__blob=publicationFile&v=4

[8] H. H. Zeineldin, E. F. El-saadany, and M. M. A. Salama, “Distributed Generation Micro-Grid Operation: Control and Protection,” in *2006 Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources*, 2006, pp. 105–111.

[9] J. Rodriguez, Ed., *Advanced and intelligent control in power electronics and drives*: Springer International Publish, 2016.

[10] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, “Control of Power Converters in AC Microgrids,” *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4734–4749, 2012, doi: 10.1109/TPEL.2012.2199334.

[11] A. Tayyebi, D. Gross, A. Anta, F. Kupzog, and F. Dorfler, “Frequency Stability of Synchronous Machines and Grid-Forming Power Converters,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1004–1018, 2020, doi: 10.1109/JESTPE.2020.2966524.

[12] G. Wang, F. Huang, Y. Yu, S. Wen, and Z. Tu, “Degradation behavior of a proton exchange membrane fuel cell stack under dynamic cycles between idling and rated condition,” *International Journal of Hydrogen*

Energy, vol. 43, no. 9, pp. 4471–4481, 2018, doi: 10.1016/j.ijhydene.2018.01.020.

[13] EUtech Scientific Engineering GmbH, *Thermolib.* [Online]. Available (1st September 2022): https://www.thermolib.de/

[14] M. J. Grimble, M. A. Johnson, J. T. Pukrushpan, A. G. Stefanopoulou, and H. Peng, *Control of Fuel Cell Power Systems*. London: Springer London, 2004.

[15] J. C. Amphlett, R. M. Baumert, R. F. Mann, B. A. Peppley, P. R. Roberge, and T. J. Harris, “Performance Modeling of the Ballard Mark IV Solid Polymer Electrolyte Fuel Cell: II . Empirical Model Development,” *J. Electrochem. Soc.*, vol. 142, no. 1, pp. 9–15, 1995, doi: 10.1149/1.2043959.

[16] H. Behret, “Karl Kordesch und Günter Simader: Fuel Cells and Their Applications, VCH, Weinheim, 1996. ISBN 3-527-28579-2, DM 248,-,” *Berichte der Bunsengesellschaft für physikalische Chemie*, vol. 100, no. 11, p. 1922, 1996, doi: 10.1002/bbpc.19961001128.

[17] F. Laurencelle *et al.,* “Characterization of a Ballard MK5-E Proton Exchange Membrane Fuel Cell Stack,” *Fuel Cells*, vol. 1, no. 1, pp. 66–71, 2001, doi: 10.1002/1615-6854(200105)1:1<66::AID-FUCE66>3.0.CO;2-3.

[18] J. C. Amphlett, R. M. Baumert, R. F. Mann, B. A. Peppley, P. R. Roberge, and A. Rodrigues, “Parametric modelling of the performance of a 5-kW proton-exchange membrane fuel cell stack,” *Journal of Power Sources*, vol. 49, 1-3, pp. 349–356, 1994, doi: 10.1016/0378-7753(93)01835-6.

[19] T. E. Springer, T. A. Zawodzinski, and S. Gottesfeld, “Polymer Electrolyte Fuel Cell Model,” *J. Electrochem. Soc.*, vol. 138, no. 8, pp. 2334–2342, 1991, doi: 10.1149/1.2085971.

[20] Woong-chul Yang, Bradford Bates, Nicholas Fletcher, and Ric Pow, “Control Challenges and Methodologies in Fuel Cell Vehicle Development,” SAE Technical Paper 98C054, Oct. 1998. [Online]. Available (1st September 2022): https://www.sae.org/publications/technical-papers/content/98c054/

[21] J. Larminie and A. Dicks, *Fuel Cell Systems Explained*. West Sussex, England: John Wiley & Sons, Ltd, 2003.

[22] V. Quaschning, *Regenerative Energiesysteme: Technologie - Berechnung - Klimaschutz,* 11th ed. München: Hanser, 2021. [Online]. Available (1st September 2022): https://www.hanser-elibrary.com/doi/book/10.3139/9783446472068

Towards Imaging-based Digital Design of Complex Functional Composites

Denis Kramer*, Joshua Simons,
Thomas Carraro, Jens Wulfsberg, …
Helmut-Schmidt-University /
University of the Armed Forces
Hamburg, German
*d.kramer@hsu-hh.de

Claudio Pistidda*, Thomas Klassen,
Maximilian Passing
Helmholtz Centre Hereon
Institute of Hydrogen Technologies
Geesthacht, Germany
*claudio.pistidda@hereon.de

Christina Krywka*, Julian P. Moosman,
Imke Greving, Silja Flenner
Helmholtz Centre Hereon
Institute of Materials Physics
Hamburg, Germany
*christina.krywka@hereon.de

***Abstract* – Functional composites are ubiquitous in technology. They allow to simultaneously optimize functional properties against multiple application demands by combining several phases, each contributing desired functions. However, the forming structure and internal interfaces govern the overall properties of the composite in complex ways. Without understanding these complex structure-property relationships, rational design of advanced functional composites is impossible. Here we present new capabilities and ambitions of the CTCentre for Functional Composites, touching on infrastructure, advanced image processing, image-based modelling, as well as a selection of use cases and applications.**

Tomography, Imaging, Composites, Advanced Manufacturing, Hydrogen Storage

I. Introduction

Composite materials are indispensable for engineering innovation. They are found in buildings (e.g, concrete), structural components of machines (e.g., carbon fibre composites) and energy storage and conversion devices (e.g., battery electrodes) to name only a few. Fundamentally, they promise to comply with complex, multi-dimensional demand-metrics by combining multiple phases, each addressing one or more of the material requirements. Typical requirements are material strength, low/high weight, high/low heat/mass transport, activity for chemical reactions and so on. In each of these cases, the emerging macroscopic properties are not only a function of the phases; they critically depend on the morphology (i.e., the distribution and interconnectivity of the phases in a composite) as well.

Hence, measuring the morphology of a composite is the first step to understand its behaviour. Todays advanced X-ray tomography platforms provide powerful, experimental access to the internal structure of composite materials. Lab-based systems provide millimetre to sub-micrometre resolution, which is well suited for a large range of composite materials. However, composites also commonly comprise structural features at the nanometre scale that demand highest resolution at synchrotron-based facilities. In addition, composite materials are often hierarchical in the sense that structural features span several orders of magnitude. Concrete is a good example: cement pastes typically have pore sizes in the micrometre range, while aggregates are millimetre to centimetre in size. This typically calls for a combination of imaging approaches to fully resolve structural features across all relevant length scales.

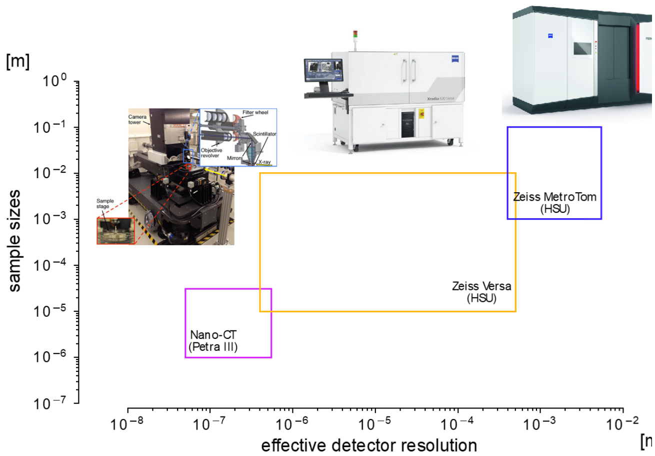
Finally, composite morphology needs to be mapped to macroscopic properties to be useful in the design of functional materials. Digital approaches to constructing these structure-property relationships are attractive to minimize the need for time consuming and costly series of experiments. Common approaches include direct numerical simulation of physical phenomena [1], mathematical homogenization approaches [2] as well as the use of machine learning [3].

Hence, an integrated approach that combines CTs, capable of resolving all relevant length-scales, with advanced data management and simulation capabilities is desirable to digitally map the structure-property relationships and accelerate design and innovation cycles.

II. Infrastructure

A. X-Ray Tomography Platforms

The DTEC.Bw CTCentre builds on two X-ray tomography facilities housed at the Helmut-Schmidt-University and a



Figures 1: Effective resolution and sample sizes of X-Ray tomography platforms.

https://doi.org/10.24405/14526

synchrotron-based platform at PETRA III in Hamburg, spanning sample sizes from tens of microns to tens of centimetres and resolutions from nanometres to millimetres (cf. FIGURE 1).

Moving large voxel sets, which can easily exceed 60 GB each, from storage to compute infrastructure and back is increasingly becoming a true bottleneck in processing tomography data. Early test data, using a single storage server and ten client nodes communicating via InfiniBand, indicates

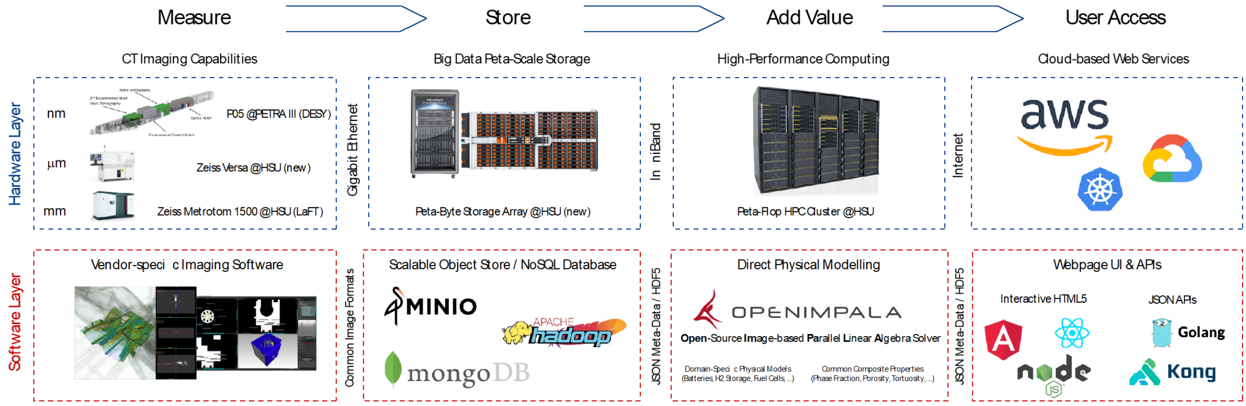


FIGURE 2: DIGITAL INFRASTRUCTURE FOR SCALABLE STORAGE AND EFFICIENT PROCESSING OF LARGE DATASETS

The two commercial, lab-based systems supplied by Zeiss provide resolution from sub-microns upwards and can image sample sizes of a few millimetre up to several tens of centimetres. The Zeiss Versa 620 produces X-rays powerful enough to penetrate several millimetre of metal whilst retaining excellent resolution across a range of X-ray energies. It is well suited to imageing samples with dimensions in the millimetre to centimetre range and resolves structural features in the micrometre domain (e.g., batteries, fuel cells, metal hydride samples, carbon fibre composites, …). The Zeiss MetroTom provides even higher energy x-rays capable of penetrating centimetres of metal and resolves internal features with sub-millimetre resolution. It is well suited to imageing samples with dimensions in the centimetre range (e.g., structural components, metal foams, additive manufacturing products, …).

A full-field X-ray microscope has been installed at the nanotomography end station at the imaging beamline P05 at the PETRA III storage ring at DESY, which is operated by the Helmholtz-Zentrum Hereon [4]. The transmission X-ray microscopy can be operated in standard absorption, Zernike phase contrast and near-field holotomography mode and offers a high temporal resolution with tomographic scan times down to 6 s and spatial resolutions below 100 nm.

B. *Data Storage and Computing*

The ability to store and manipulate large datasets is fundamental to the centres ambition. Further, meaningful scalability requires a high level of automation for storage, retrieval, compute and visualisation elements of data processing workflows. The centre implements a tiered digital infrastructure (cf. FIGURE 2) to address these requirements.

A key element is the co-location of a PetaByte object storage array with the new high-performance computing cluster (HPC) HSUper [5] at HSU. The storage array has direct access to the InfiniBand interconnect of the HPC cluster for maximal data throughout. The solution is based on Ceph [6], an open-source, distributed storage system with its own high-performance Rados API for distributed read/write access.

that the hardware side integration of the storage array with the HPC interconnect enables single throughput of a few GB/s in read and write with good scalability for concurrent read operations (cf. TABLE 1). The good scalability of the concurrent read operations highlights the benefits of a distributed storage strategy: there is no single point that all traffic has to pass through. This is an excellent match to the distributed compute model of distributed memory HPC clusters, where individual MPI processes operate on subsets of a larger compute task. Individual MPI processes can directly communicate with individual storage servers hosting relevant parts of the total dataset. The price that has to be paid for this I/O scalability is the need to custom-code the I/O operations of scientific software with the storage cluster using the Rados API provided by Ceph rather than a file system.

TABLE I: DATA THROUGHPUT OF A CEPH STORAGE TEST SETUP.

Single Write	*Random/Sequential Single Read*	*Concurrent 10x Write*	*Random/Sequential Concurrent 10x Read*
~1.1 GB/s	2.5 GB/s	~3.8 GB/s	~13.8 GB/s

It is a key ambition of the CTCentre to add value by overlaying tomographies with physical simulations to extract application relevant characteristics and properties, ideally in an automated way. Therefore, it is attractive to utilise HPC clusters and distributed compute strategies to directly compute on tomography voxel sets as these can be easily subdivided in space. However, this requires specialised codes developed with parallel computing in mind.

One such code is the Open-Source Image-based Parallel Linear Algebra Solver (OpenImpala) [7], which has been designed from the ground up to take advantage of parallel HPC environments to solve PDE-based models directly on voxel sets, circumventing the need for meshing, which is often a manual and error-prone task. OpenImpala has been ported and optimised to the new HPC infrastructure at HSU. FIGURE 3 shows a scaling analysis of a diffusive mass transport problem in random packings of spheres with domain sizes ranging from 10^6 to 10^8 voxels. These Poisson-type problems allow to extract important characteristics of

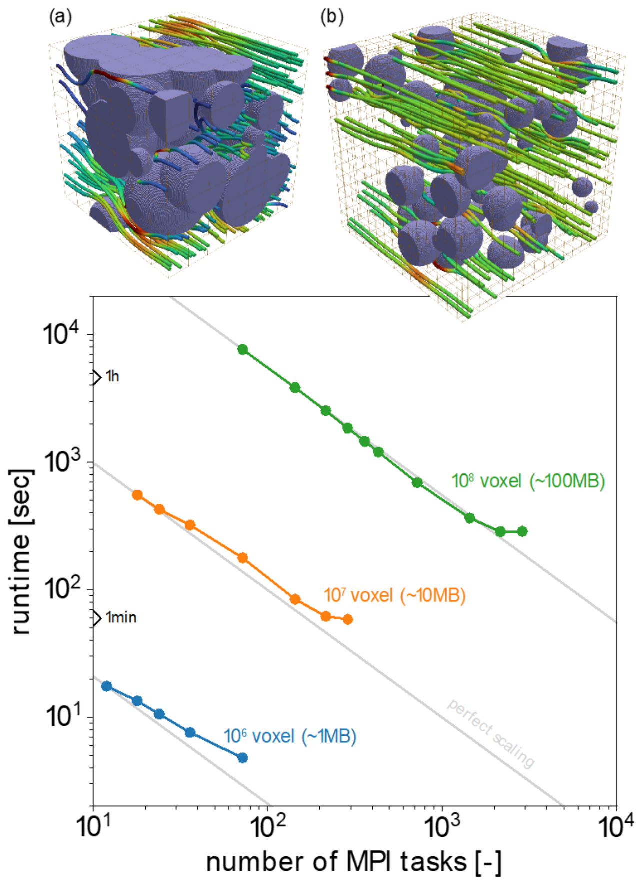


FIGURE 3: PARALLEL PERFORMANCE OF A DIFFUSIVE MASS TRANSPORT PROBLEM IN RANDOM SPHERES SOLVED ON HSUPER WITH OPENIMPALA; (A) DOMAIN WITH 10^7 VOXELS, (B) DOMAIN WITH 10^8 VOXELS; VALUES IN BRACKETS INDICATE DATASET SIZE ASSUMING AN 8BIT GRAYSCALE; LIGHT GRAY LINES VISUALIZE REDUCTION IN COMPUTE TIME WITH PERFECT PARALLELISATION.

composites such as effective transport parameters relevant for mass and heat transport, but also for elasticity problems. The computational domains comprising 10^7 and 10^8 voxels are shown in (a) and (b), respectively. Streamlines indicate the mass flux through the complex geometries with green/red representing low/high fluxes. The domains were subdivided into boxes, indicated by the brown grids lines, and the Poisson equation solved in parallel in each of these boxes utilising a varying number of processors (i.e., MPI tasks) on HSUper.

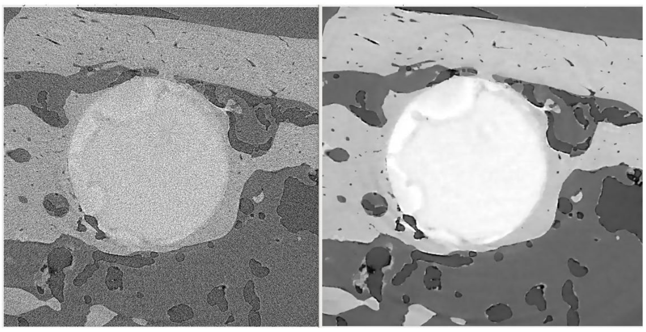


FIGURE 5: MACHINE-LEARNING BASED DENOISING OF AN ABSORPTION CONTRAST MICROTOMOGRAPHY SCAN OF A MG10GD IMPLANT IN BONE. LEFT: RECONSTRUCTION BEFORE DENOISING. RIGHT: DENOISED IMAGE USING DUAL DENOISING APPROACH WITH A NON-LOCAL MEANS FILTER APPLIED PRIOR TO NOISE2INVERSE.

The FIGURE 3 shows the required compute time for three voxel sets as a function of the number of utilised parallel processes. For larger voxel sets, OpenImpala shows almost perfect parallel performance up to the limit of one MPI process per box beyond which a reduction in compute time can only be expected by choosing smaller box sizes and more boxes, respectively.

Tomographic voxel sets can comprise up to 10^9 or even close to 10^{10} voxels due to the availability of CMOS detectors with 1024x1024 or 2048x2048 pixels. We expect to be able to directly solve Poisson-type problems on these very large domains within a matter of hours utilising around 2% of the available compute power at HSUper (i.e., 1000 cores). To put this into perspective, solving such problems on a domain comprising 10^8 voxels on a single CPU would almost take a week.

C. *Visualisation and Access*

Visualisation and data access is a vital part of the overall strategy to add value for external collaborators. These parts of the ecosystem will be implemented in a later phase of development and comprise APIs and web-interfaces to access and visualise tomography and simulation data alike.

III. APPLICATIONS AND USE CASES

A. *Advanced Image Processing*

1) *Machine-Learning for Noise reduction*

For in situ as well as high-throughput experiments, tomographic scan times are a limiting factor. Using a mixed-scale dense convolutional neural network [8], the noise in the

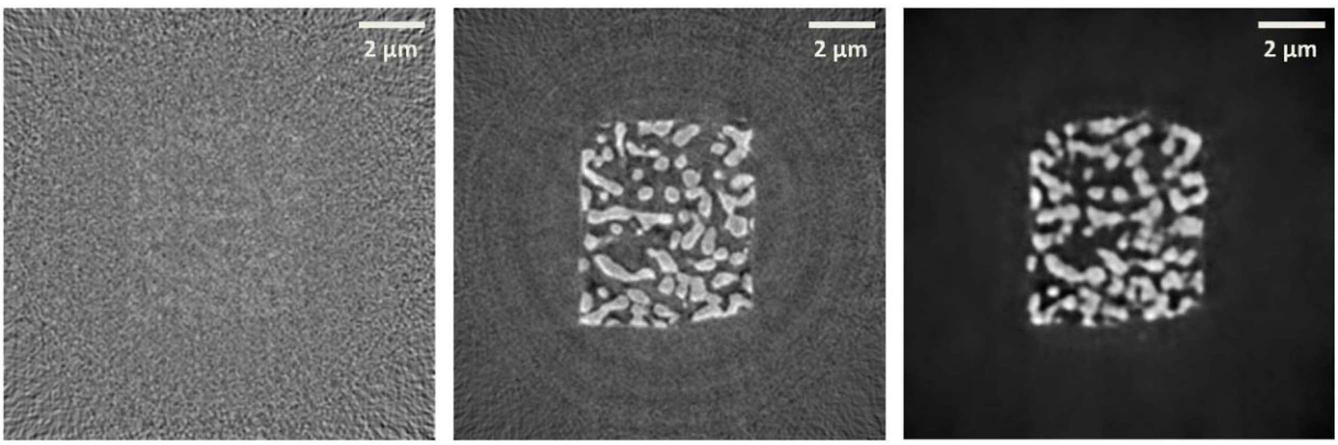


FIGURE 4: MACHINE-LEARNING BASED DENOISING OF NANOPOROUS GOLD WITH A BINARY STRUCTURE USING HIGH- AND LOW-QUALITY ABSORPTION CONTRAST NANOTOMOGRAPHY SCANS. LEFT: INPUT DATA FROM A FAST SCAN WITH VERY HIGH NOISE. MIDDLE: TARGET DATA FROM A LONG HIGH-QUALITY SCAN. RIGHT: DENOISED OUTPUT FROM THE NEURAL NETWORK. IMAGES TAKEN FROM [9].

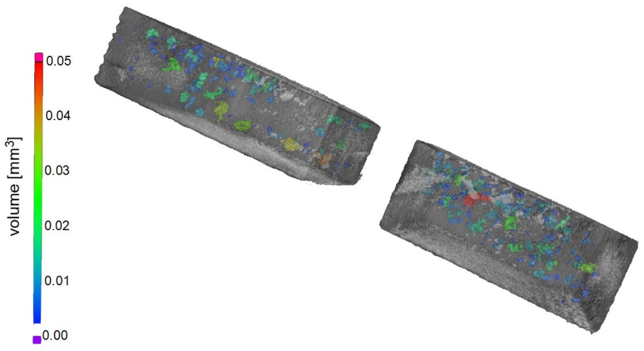


FIGURE 6: POROSITY IN A PRINTED STAINLESS STEEL SAMPLE; VOIDS ARE COLORED BY VOID VOLUME.

reconstructed tomogram could be reduced considerably or even eliminated. Here, a long high-quality scan is acquired before (or after) the *in situ* experiment and short scans during the *in situ* experiment. The network is then trained on a short and a corresponding long scan which acts as a ground truth, see FIGURE 4 where a nanoporous gold structure was scanned using absorption contrast nanotomography [9]. With this approach, fast scans in the order of about 3 min can produce a similar image quality as high-quality scans which take at least 15-30 min. The right image in FIGURE 4 shows that the noise is completely eliminated in the reconstruction. This is because the neural network learns the `real' structures and does not reproduce the random noise. Another unsupervised approach is Noise2Inverse where, assuming a sufficient number of projections have been acquired, the projections of a single tomographic scan are split in two independent stacks resulting in two reconstructions from the same measurement with identical sample information, but uncorrelated noise [10]. The Nosie2Inverse approach denoises images without introducing an additional blurring and allows to resolve fine structures down to very few pixels (cf. FIGURE 5).

2) Super-resolution

To understand the functional behaviour of composites, their microstructure must be studied, and imaging techniques are central in this area. However, composites are often heterogeneous and require quantification of small features over representative volumes. Therefore, resolution of microscopy image data is critical in the study of composites. Microscopy equipment is time consuming and expensive to operate, and resolution, i.e., the size of the acquired image voxel, is indirectly proportional to the volume of tomography. High resolution is required to capture small features of the composites but limits the maximum volume that can be imaged. Direct simulation at the microscopic level to model composite behaviour is not possible for macroscopic volumes. For example, spatially resolved models discretized with finite differences, as shown above can be solved numerically with voxels on the order of 10 nanometres only for volumes of a few micrometres. For this reason, multiscale models are essential to model functional properties at the macroscopic level. In the case of multiscale models, the calculations performed at the microscopic level need only be statistically representative. That is, they must be large enough to capture the typical variations within a macroscopic volume. Given the physical limitations of a tomographic technique, there is a trade-off between a large representative volume and well-resolved small features within that volume. Machine learning techniques can be used to overcome the inherent limitation of

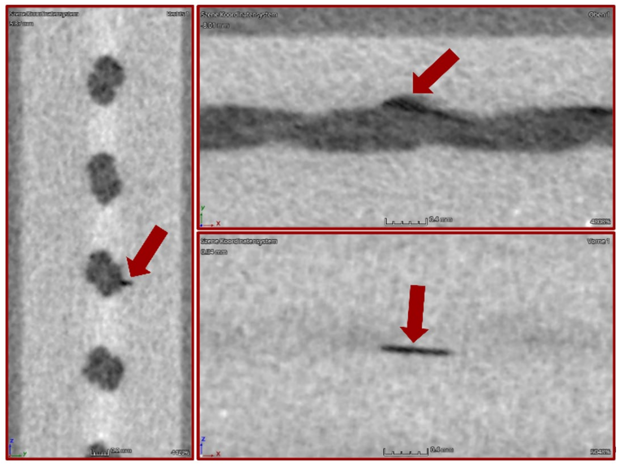


FIGURE 7: INTERFACE RUPTURE BETWEEN RUBBER AND CORD.

the imaging technique used, as recent work has shown [12]. These techniques are called super-resolution because they improve the resolution of tomographic images. Various machine learning techniques have been used for this purpose [12]. For example, in [13], the use of generative adversarial networks for crack detection in aged cathode particles of lithium ion cells was demonstrated. Different techniques for super-resolution of SEM data of cathode materials were compared. The neural networks used for super-resolution must be trained with high- and low-resolution data. It is shown that the high- and low-resolution data pairs do not have to match. In fact, using down-sampled images from high-resolution images is not the best way to perform super-resolution, as it is shown that artificially generated low-resolution images cannot be compared to measured low-resolution images. At the CTcenter, images with different resolution can be acquired taking full advantage of the CT platforms spanning several orders of resolution. Therefore, the investigation of super-resolution techniques using images acquired with different instruments is planned with the aim to reduce the demand for synchrotron-based measurements.

B. Technology Research

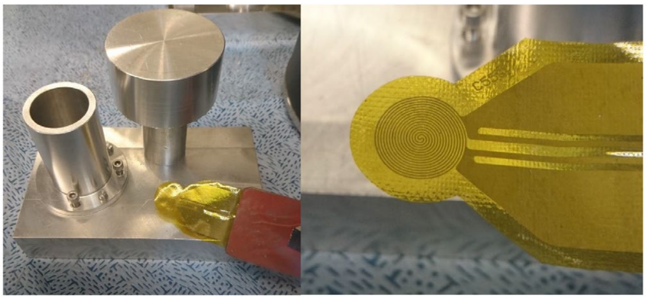
1) Advanced Manufacturing

Laser powder bed fusion (LPBF) is a popular additive manufacturing technique, where high power lasers fuse powdered alloys. X-Ray tomography enables the investigation of adhesion defects between the melt lines. An example of void detection in printed stainless steel is shown in FIGURE 6. Of special interest are the morphology, distribution, and quantity. Manufacturing results of laser powder bed fusion of metals are improved by researching the effect of process parameters on adhesion defects. Optimal process parameters result in samples without adhesion defects.

Defect detection and analysis of manufactured components after service life is another important area of interest. As an example, FIGURE 7 shows results of long-term cyclic tests of air spring sleeve configurations used in the automotuve industry. A defect formed after testing is marked by red arrows. Points of weakness can be identified with non-destructive X-ray imaging and provide hints for further improvement in manufacturing.

2) Hydrogen Storage

One of the most challenging tasks in designing a metal hydride tank is to achieve a good heat management of the



FIGURES 8: EXPERIMENTAL SETUP FOR THE TPS "HOT DISC" MEASUREMENTS (LEFT) AND THE USED KAPTON SENSOR (RIGHT)

whole system. Due to the endothermic desorption and the exothermic absorption, great amounts of heat must be transported inside and outside the powder bed, respectively. The heat transport inside a powder bed is described by the effective thermal conductivity. For investigating how the material particle sizes and particle shapes influence the material thermal conductivity, powders of the Mg alloy AZ91 were utilized as model systems. The thermal conductivity was measured through the hot disk transient plane source method (TPS 1500 from Hot Disk AB).

The as received Mg based alloy was milled under an argon atmosphere using a high-energy ball mill. The used mill is an industrial Simoloyer-CM08 ball mill (ZOZ GmbH). The milling time was set to two hours and the ball to powder ratio was 1:20. During the milling a speed program of a periodic repetition of 700 rpm for 30 s and 300 rpm for 30 s was chosen. Milling tools of 100Cr6 steel with a diameter of 5 mm were used. No other materials were added to the mill. Three batches of about 350 g Mg waste powder were produced. After milling the Mg based alloy, the powder was sieved for one hour in a sieving machine (Analysette 3 Pro from the company FRITSCH). The mesh sizes of 63 µm, 125 µm and 355 µm were chosen. The obtained powder fractions were labeled based on the average diameter of the particles (dp) as: 1) Batch 1 (B1) dp<63 μm; 2) Batch 2 (B2) 63 $\mu m \leq dp$<125 μm; 3) Batch 3 (B3) 125 $\mu m \leq dp$<355 μm; 4) Batch 4 (B4) 355 $\mu m \leq dp$. The effective thermal conductivity for the different powder batches B1–B4 is measured with isotropic and anisotropic settings. In FIGURE 8 the measured effective thermal conductivities are compared with each other. It is noticeable, that the isotropic measured results are in the same range for the batches B1–B3 of about 0.18 W/mK, whereas B4 has a more than twice as high thermal conductivity of 0.43 W/mK. This benchmark data will help to verify the image-based determination of effective transport parameters using the highly parallel Poisson solver provided by openImpala.

IV. CONCLUSION AND OUTLOOK

The CTCentre has already made significant strides towards image-based design of functional composites. The required digital infrastructure is in place and operational. Two of the three CT platforms are operational, and the remaining micro-CT will be delivered in the next months. Software assets such as OpenImpala or image-processing codes are currently under development or are integrated with the digital infrastructure. In the next phase, we look forward to complete the lab-based and digital infrastructure before shifting the focus towards applications and external access.

ACKNOLODGEMENT

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project CTCentre].

REFERENCES

[1] J. Le Houx, D. Kramer, *Energy Reports* **7** (2021) 9.

[2] A.L. Kalamkarov, *Appl. Mech. Rev.* **62**(3) (2009) 1.

[3] C. Qiu, J. Yang, *ACS Symp. Series* **1416**(4) *(2022) 65.*

[4] M. Ogurreck *et al. J. Phys. Conf. Ser.* **425** (2013) 182002; M. Ogurreck *et al.,* J. Phys. Conf. Ser. **849** (2017) 012056; S. Flenner *et al.*, *Microsc. Microanal.* **24** (2018). 148.

[5] https://www.hsu-hh.de/hpc/en/hsuper-2/.

[6] https://ceph.io

[7] J. Le Houx, D. Kramer, *SoftwareX* **15** (2021) 100729.

[8] D. Pelt, K. Batenburg, J. Sethian, *J. Imaging* **4** (2018) 128; D. Pelt, J. Sethian, *PNAS* **115** (2018) 254.

[9] S. Flenner *et al.*, J. Synchrotron Rad. **27** (2020). 1339.

[10] A. Hendriksen *et al.*, *IEEE Trans. Comput. Imaging* **6** (2020) 1320.

[11] Z. Wang *et al.*, *IEEE Trans. Pattern Anal. Mach. Intell.* **43** (2021) 3365.

[12] X. Yu, F. Porikli, *Proc. Europ. Conf. Comp. Vis.* (2016) 18; C. Ledig *et al.*, Proc. IEEE Conf. Comp. Vis. (2017) 105; L. Fan *et al.*, Nanomaterials **11** (2021) 3305.

[13] O. Furat *et al., npj Comput. Mater.* **8** (2022) 68.

Hydrogen in stationary applications: Coupling the electricity, gas and mobility sectors (Digi-HyPro)

Julián Puszkiel*, Myriam Covarrubias Guraneros, Lukas Fleming , Thomas Friedrich Johannes Kaufmann, Phillip Krause, Jan Warfsmann, Eike Wienken, Lukas Wildner, Matthias Schulze, Thomas Klassen, Julian Jepsen
Faculty of Mechanical Engineering, Institute of Material Engineering, Helmut-Schmidt-University, Hamburg, Germany
**puszkiej@hsu-hh.de*

Julián Puszkiel*, Myriam Covarrubias Guraneros, Lukas Fleming, Thomas Friedrich Johannes Kaufmann, Phillip Krause, Jan Warfsmann, Eike Wienken, Lukas Wildner, Helge Kutzner, Gökhan Gizer, José María Bellosta von Colbe, Klaus Taube, Thomas Klassen, Julian Jepsen
Institute of Hydrogen Technology, Helmholtz-Zentrum Hereon, Geesthacht, Germany
**julian.puszkiel@hereon.de*

Homa Hamedi, Torsten Brinkmann*
Institute of Membrane Research, Helmholtz-Zentrum Hereon, Geesthacht, Germany
**torsten.brinkmann@hereon.de*

***Abstract* – Global warming and continuous fossil fuel depletion are worldwide phenomena that pose challenges such as the reduction of greenhouse gas emissions and the further exploitation of renewable energy sources. Nevertheless, the transition from fossil fuels to a renewable-energy-based economy demands more innovative solutions and developments such as the Power-to-Gas-to-Power (PtoGtoP) idea. Hydrogen is considered one of the clean energy carriers in the concept of PtoGtoP. However, this strategy still suffers from several challenges, like intermittent inflows of energy, high costs, and rather low energy efficiency due to the losses during conversion and storage. The goal of the Digi-HyPro (Digitalized Hydrogen Process Chain for the Energy Transition) project is to develop an efficient and modular PtoGtoP system. The concept of this modular system, called Smart-Energy-Transform-Unit (SET-Unit), aims to design a decentralized and scalable system for clean energy demands spreading across different locations. The SET-Unit serves to optimize the connections between renewable sources and the current power and gas grid demand. Applying this concept, hydrogen generated by an electrolyzer can be stored compactly and safely in a metal hydride storage system or fed into the natural gas grid. On-demand, hydrogen can also be taken from the intermediate storage facility or the gas grid by applying gas separation techniques and can be delivered (i) to an integrated fuel cell to produce power or (ii) to a metal hydride compressor to provide hydrogen for the mobility sector (trucks, cars, trains, etc.). Component and system level simulations are performed to design, develop and optimize the individual and overall integrated system. These digital models draw critical data from experiments and are validated using prototype setups. For this purpose, experimental setups on a laboratory scale of 10 kWel, and an intermediate scale of 50 kWel are part of the Digi-HyPro project's plan. This multidisciplinary investigation involves the optimization of the digital SET-Unit system with experimental demonstrations in kWel ranges. Final scalability studies in the industrially relevant MWel range can pave the way to an efficiently networked green energy system.**

Keywords – Green Hydrogen Production, Sector Coupling, Metal Hydrides, Hydrogen Purification, Gas-Grid-Based Hydrogen Storage

NOMENCLATURE

AB_2-alloy	Room temperature hydride forming alloy based on Ti-Zr (A) and Cr-Mn-V-Fe (B)
AB_5-alloy	Room temperature hydride forming alloy based on La-Ce-Pr-Nd (A) and Ni-Mn-Co-Al (B)
AEM	Anion Exchange Membrane
Digi-HyPro	Digitilized Hydrogen Process Chain for the Energy Transition
EL	Electrolyzer
ENG	Expanded Natural Graphite
FC	Fuel Cell
FEM	Finite Element Modeling
HTF	Heat Transfer Fluid
MH	Metal Hydride
NG	Natural Gas
PEM	Proton Exchange Membrane
PSA	Pressure Swing Adsorption
PtoGtoP	Power-to-Gas-to-Power
RT	Room Temperature
SET-Unit	Smart-Energy-Transform-Unit
SIM	System Integration Modeling
TRL	Technology Readiness Level

I. INTRODUCTION

The worldwide dependency on non-renewable fossil fuel resources [1], the increase in energy demand [2], and the rise in the earth's average surface temperature owing to global warming [3] request the short-term introduction of renewable energy sources [4]. Hydrogen is considered one of the clean energy carriers required to implement the PtoGtoP concept. However, this strategy still suffers from several challenges, like intermittent inflows of energy, high costs, and low energy efficiency (15 to 40 %) due to the losses during conversion and storage [5]. One of the main bottlenecks to improve the

https://doi.org/10.24405/14527

efficiency of integrated systems based on hydrogen technology is to incorporate an efficient method to store hydrogen [6]. Hydrogen is an extremely light gas at normal pressure and temperature and is difficult to store. For compact storage, e.g., in vehicles, high pressures of up to 700 bar are required. Alternatively, hydrogen can be liquefied in an energy-intensive process in which about 30 % of the energy content of the hydrogen must be used for liquefaction. An energy-efficient and compact solution is hydrogen storage in MH compounds: compared with high-pressure hydrogen storage, twice the volumetric capacity (> 50 kg H_2/m^3) is achieved at considerably lower pressures typically between 10–50 bar [7]. Especially for stationary applications in areas, where space is limited and expensive and high safety restrictions apply, MH-storage has a decisive advantage over other storage methods. The MH-storage is stable over the long term, and is the safest option: Even in case of an unforeseen hazard, hydrogen is not released catastrophically, but only at a certain controlled rate, because release consumes heat. In addition, the usually low storage pressures are easy to handle. Thus, legal requirements are less demanding. Furthermore, the MH compound does not cause any further side reactions. Hydrogen can be stored 100 % reversibly in MH independently of the time scale and the size of the system [5, 6, 7].

The Digi-HyPro (Digitalized Hydrogen Process Chain for the Energy Transition) project aims to develop an efficient and modular PtoGtoP system based on the storage and compression of hydrogen in MH units. The concept of this modular system, called Smart-Energy-Transform-Box (SET-Unit), proposes a novel efficiency-maximized strategy to design a decentralized and scalable system for energy demands spreading. The SET-Unit serves to optimize the connections between renewable sources and the current power and gas demand. FIGURE 1 shows the concept of the set box connecting the existing grids and also the visualization of the development of a digital twin for optimization purposes.

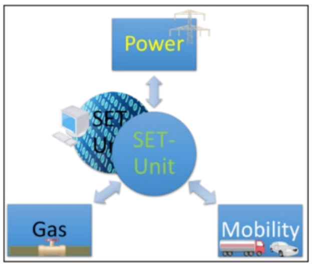


FIGURE 1: CONCEPTUAL VISUALIZATION OF THE SET-UNIT.

FIGURE 2 shows a simplified flow diagram of the SET-Unit concept, where the main components (FC, EL, MH-storage, compressor, gas separation process, and heat exchange management) and streams are included. As shown, the system is designed to utilize and provide electrical power during the low and high demand hours, respectively. Furthermore, it is also possible to mitigate and stabilize the intermittency of power generation from renewable sources. Applying this concept, hydrogen generated by the EL can be stored compactly and safely in the MH-storage unit, or sent to the MH-compressor unit for utilizing it in the mobility sector. On-demand, the hydrogen can be separated from the mixed gas grid (natural gas + hydrogen) by a membrane gas separation unit combined with a pressure swing adsorption process [8, 9]. Then, hydrogen can be delivered to the integrated FC device to produce electrical power or be stored in the MH-storage unit, or even delivered to the MH-compressor unit. The system can be designed to gain efficiency through the recycling of the waste heat (Q_w) coming from the EL, the FC, from the exothermic hydrogen absorption in the MH-storage and compressor units, and also from the heat generated in the gas separation process. An efficient heat exchange management allows recovering heat (Q_R) and re-using it for the endothermic hydrogen release from the MH-based units on demand.

In the Digi-HyPro projects, bottom-up as well as top-down strategies are applied to develop the SET-Unit concept. On the one hand, the bottom-up approach consists of units and subsystem-level model developments and their experimental set-up designs and optimizations. On the other hand, the top-down approach consists of the conceptual design and development of the whole SET-Unit and final realization considering an optimized automatic control strategy.

Applying the bottom-up strategy, the units to be developed and designed are the gas separation process based on membranes, and the MH-storage and -compressor ones. In the case of MH-storage and compressor units, depending on the material and application, these can result in a TRL 3 to 8. The separation of H_2 from gas mixtures using membranes is an established technology in the chemical and petrochemical industry with a TRL between 4 and 9, and typical H_2 purities in the range from 95 to 99 vol% are reached [8]. FC and EL devices are already in the market in the ramp-up phase and have already reached a TRL 8 to 9. Thus, FC and EL implementation lies in the integration with MH-storage, MH-compressor, and membrane gas separation units, but not in the development of such devices themselves. The subsystem level involves the coupling of MH-Storage and EL, MH-storage and FC, MH-compressors and EL / MH-storage as well as the combination of the membrane separation process. For this purpose, experimental setups on a laboratory scale of 10 kWel, and an intermediate scale of 50 kWel are proposed.

By implementing the top-down strategy, it is possible to bring in the complex and dynamic interaction between the components of the system. Above all the heat exchange management which basically gives the optimized process strategy for the interactions. Finally, proceed with scalability investigations of the SET-Unit on the MWel range.

The whole analysis and investigation of the SET-Unit concept can pave the way to innovative and efficient networked green energy systems.

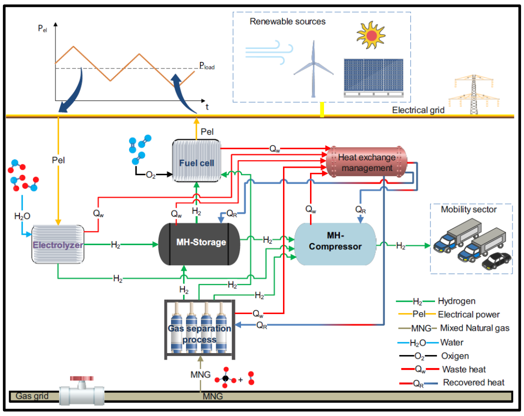


FIGURE 2: FLOW DIAGRAM OF THE SET-UNIT CONCEPT.

II. EXPERIMENTAL AND MODEL DESCRIPTION

In this section, the experimental procedures and modeling descriptions are presented. In the case of the MH material for storage and compression, the synthesis, characterization, and surface modification techniques are described. The software, the physics included, and the relevant parameters introduced in the models are shown for the FEM and SIM.

A. Characterization and surface modifications of MH forming alloy for hydrogen storage

The commercially available metal alloy HydralloyC5 (AB2-alloy; Ti0.95Zr0.05Mn1.46V0.45Fe0.09) was purchased from GfE (Gesellschaft for Elektrometallurgie). The particle size of the Hydralloy C5 was reduced from 2-10 mm down to ≤ 4 mm before use with a Retsch BB50 jaw crusher. ENG (particle size 5 µm; SGL-Carbon) and Aerosil R805 (Evonik Operations) have been used as received. For the experiments, the HydralloyC5 has been used as pure material or in combination with ENG and Aerosil. In a typical experiment, 10 g of Hydralloy was placed with ENG (1 g; 10 wt%) and optionally Aerosil R805 (0.02 g; 0.2 wt%) in a round-bottom flask and mixed for 2 h with a mechanical stirrer at RT. The characterization of the sample was done with an in-house produced Sieverts apparatus. In addition to the hydrogen capacity, the temperature and strain were also measured in situ by attaching a strain gauge and thermocouple to the sample holder. In a typical experiment, the sample holder was filled with about 8 g of sample, and the conditions were set to 40 °C / 40 bar hydrogen pressure (absorption) and 40 °C / 5 bar hydrogen pressure (desorption). The hydrogen capacity and temperature behavior of the samples were evaluated during 50 hydrogenation-dehydrogenation cycles, while the stress behavior was evaluated for 7 to 16 hydrogenation-dehydrogenation cycles.

B. Synthesis and Characterization of MH forming alloy for hydrogen compression

$TiCr_{1.9}$ alloy was synthesized by using and Edmund Bühler MAM-1 arc melter. The desired mass of Ti and Cr foils were weighed to form the $TiCr_{1.9}$ composition. In total, 4 g of material was placed into the melting chamber. Ti and Cr were melted together with an electric arc and cooled to room temperature. The prepared alloy was inverted and remelted five times to obtain a homogeneous product. The synthesized alloy was crushed into small pieces and stored in air. Diffraction patterns of as-synthesized and hydrogenated samples were collected using a Bruker D8 Discover diffractometer, equipped with a 2D Vantec detector. Cu Kα radiation was used and the Bragg angle was chosen between 30-80º. Phase analysis of as-synthesized and hydrogenated samples was carried out via MAUD software with the Rietveld approach [10, 11]. Hydrogenation of the samples for the diffraction experiment was carried out using a Sieverts apparatus, Hera (QC J4G 1A1, Canada) [12]. The reactor with the hydrogenated sample was cooled to the liquid nitrogen temperature for ~30 minutes followed by the evacuation of the cooled reactor for ~1 minute. Then, the sample was exposed to air and further kept at liquid nitrogen temperature for 30 minutes. The reactor was at that moment opened to air, and the diffraction pattern of the sample was collected immediately.

Pressure composition isotherms were collected using a Sieverts apparatus PCTPro-2000 (Hy-energy LLC). 2 g of alloy, cut into small pieces, were placed in the sample chamber. For activation, the sample was firstly evacuated at 8 ºC, and hydrogenated under 120 bar of H_2 at room temperature. Pressure-Composition isotherms were collected at five different temperatures: 15 ºC, 5 ºC, 0 ºC, – 5 ºC and –10 ºC. Enthalpy and entropy of the sample were experimentally calculated, and the dependence of equilibrium pressure against temperature was plotted using using the van't Hoff equation.

C. Finite element modeling description

The modeling of the MH-storage and compressor vessels was performed using the FEM software COMSOL 5.6. It includes the modeling of heat, momentum and mass transfer. The most important assumptions for the modeling of such MH-based vessels were: 1. the hydride bed was modeled as isotropic and 2. local thermal equilibrium between the solid particles of the hydride bed and the gas phase. The hydrogen was modeled as an ideal gas and the expansion of the metal hydride due to the absorption of hydrogen was not taken into account. To model the transport of hydrogen, in the case of the MH-storage vessel, Darcy's law was applied, while for the MH-compressor vessels, the Brinkman equation was utilized. In both cases, the thermodynamic behavior of the MH compounds was described by the van't Hoff EQUATION 1:

$$p_{eq} = exp(\Delta H/(R * T) - \Delta S/R) \quad (1),$$

where, p_{eq} [bar] represents the equilibrium pressure of the MH-M system, ΔH [kJ/mol H_2] and ΔS [J/mol H_2 K] are the enthalpy and entropy changes, T [K] is the temperature, and R [J/ mol K] the ideal gas constant.

The kinetic behavior of the hydrides was implemented by applying the differential form of the separable variable EQUATION 2 [13].

$$d\alpha/dt = K(T) * F(p, peq) * G(\alpha) \quad (2),$$

where, α represents the hydrogen absorbed/desorbed fraction, i.e., mass of hydrogen absorbed during the process over the maximum reached hydrogen mass, $K(T)$ is the temperature functionality described by the Arrhenius's dependency, $F(p, p_{eq})$ is the pressure functionality dependent on the operative pressure and the equilibrium pressure p_{eq}, and $G(\alpha)$ is the description of the rate-limiting step of the reaction.

TABLE I shows the metal hydride forming material properties used in the MH-storage and compressor vessel simulations:

TABLE I: MATERIAL PROPERTIES FOR FEM SIMULATIONS OF MH-STORAGE AND COMPRESSOR VESSELS

Properties	*Hydralloy C5*	*Ref.*	*AB_2-Alloy*	*Ref.*
ρ_{metal}	6379 [kg/m³]	This work	6240 [kg/m³]	[18]
wt_{max}	1.1-1.2 [wt%]	This work	1.4 [wt%]	[18]
ΔH_{Abs} ΔH_{Des}	- 22.3 [kJ/mol] 28.4 [kJ/mol]	[14]	- 22 [kJ/mol] 24 [kJ/mol	[18]
ΔS_{Abs} ΔS_{Des}	-96 [J/mol K] 112 [J/mol K]	[14]	- 107 [J/mol/K] 110 [J/mol/K]	[18]
A_{Abs} A_{Des}	109.4 [1/s] 14.96 [1/s]	[15]	107 [1/s] 520 [1/s]	[19]
$E_{A,Abs}$ $E_{A,Des}$	19.5 [kJ/mol] 15 [kJ/mol]	[15]	14 [kJ/mol] 20 [kJ/mol]	[19]
d_P	23 [µm]	[15]	15 [µm]	[15]
k_s	1 [W/(m K)]	[16]	1 [W/(m K)]	[16]
Cp_s	500 [J/(kg K)]	[17]	500 [J/(kg K)]	[17]

In the following subsections, modeling details of the MH storage and compressor vessels are provided, i.e., geometries and operative conditions.

1) MH-storage vessel

In FIGURE 3, an example of the simulated geometry of the MH-storage vessel including 16 fins for improved heat transfer, and a description of the components can be seen. The modeling was carried out in a 2D geometry to change the number of fins and to analyze the effect on the temperature inside the hydride bed and therefore the hydrogen release. All simulations were run with an automatically generated mesh with adequate quality. During the work, different numbers of fins (0, 4, 8, 12, 16) and the heat distribution inside the storage vessel were considered.

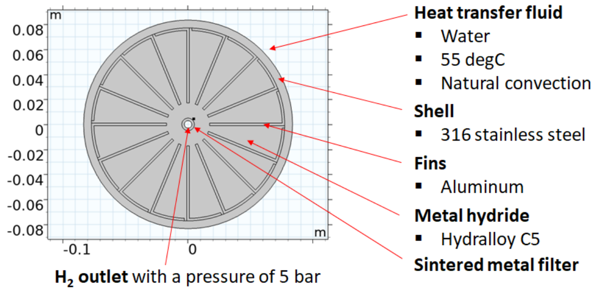


FIGURE 3: GEOMETRY AND COMPONENT DESCRIPTION OF THE MH-STORAGE VESSEL.

For all simulations, the initial temperature was set at 20 ºC and natural convection flow on the vessel hull was considered with an external temperature of 55 ºC (FIGURE 3). The initial pressure condition in the hydride bed was set at 38 bar of hydrogen and the final pressure at 5 bar of hydrogen (FIGURE 3). Such operative conditions were taken as parameters for coupling the MH vessel with an electrolyzer (initial pressure and temperature conditions) and a fuel cell (final temperature and pressure conditions). As MH-storage material, Hydralloy C5 was used due to its adequate thermodynamic and kinetic behavior for the design of such a MH-storage reservoir. TABLE I shows the most relevant parameters of Hydralloy C5 used for the simulation of the dehydrogenation process.

2) MH-compressor vessels

A two-stage MH-compressor was modeled. The key components of an MH-compressor are the pressure vessels and the MH material. In this case, they consist of a cylindrical hull made of stainless steel, which is filled with metal powder and heated and cooled by an external heat transfer fluid (HTF). A sintered filter improves the distribution of hydrogen into the metal bed. Taking into consideration the swelling behavior of the metal hydride bed upon hydrogenation [20], the internal volume of the reservoir was calculated so that the MH material occupied 60-80 % of the internal volume providing free space for the MH material expansion [21]. Each stage consists of a pressure vessel, one for the low-pressure stage and the other for the high-pressure stage. The compressor was modeled in a 2D geometry, and a proper mesh quality was used for the simulations.

The model domain and its most important features are shown in FIGURE 4. The compression cycle was modeled as a batch process.

In the first stage, the following steps took place: inlet of hydrogen into the vessel, exothermic absorption of hydrogen into the metal hydride bed, while the vessel is cooled, closing the inlet and using the sensible heat of the MH-bed to increase the equilibrium pressure of the reaction and endothermically desorbs the hydrogen at a higher-pressure level at this elevated temperature. These steps were repeated in the second stage to further increase the hydrogen pressure.

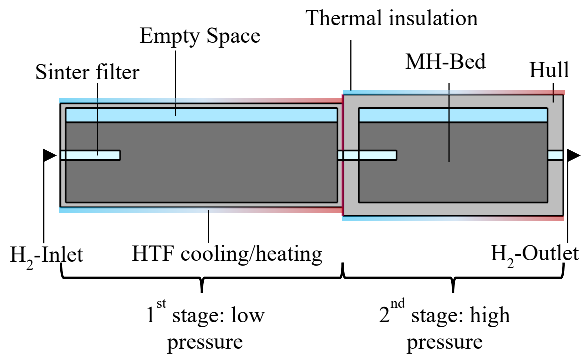


FIGURE 4: GEOMETRY AND COMPONENT DESCRIPTION OF THE MH COMPRESSOR VESSELS.

In this case, Hydralloy C5 was used as the MH-material in the first low-pressure stage and an AB2-material reported previously was employed for the second high-pressure step[18, 19]. The most important properties of these materials can be found in TABLE I.

D. System simulation

In the following subsection, the main modeling considerations for the system simulation of PEM EL and PEM FC coupled with MH in 0D geometry are provided.

1) EL-MH-storage coupling

The two dynamic 0D models (MH tank and PEM EL) were created using Aspen Custom Modeler® V11 and took into account the equations for mass and energy conservation, chemical reaction kinetics, and thermodynamic properties.

The cell voltage, $V_{cell}[V]$, of the PEM EL model was calculated according to EQUATION (3):

$$V_{cell} = V_0 + \eta_A + \eta_B - \eta_C + \eta_I \quad (3),$$

where, V_0 is the reversible cell voltage (V_{rev}^0) defined by EQUATION (4), η_A and η_C are the anodic and cathodic activation overpotentials accounting for the kinetic, diffusion, and crossover losses, η_B accounts for the overpotential of the electrolyte layer due to the membrane proton conductivity and η_I describes the overpotential caused by interfacial contact and electronic resistances [22].

$$V_{rev}^0 = \triangle G_R^0/(2 * F) = 1.229\ V \quad (4),$$

where $\triangle G_R^0$ is the standard Gibbs free energy of formation of water [kJ/mol] and F is the Faraday constant, 96485.3 [C/mol].

The model also provides the cell efficiency ε_{cell}^{HHV} calculated according to the EQUATION 5:

$$\varepsilon_{cell}^{HHV} = \frac{\triangle H_R^0 * \dot{n}_{H_2}}{P_{DC}} = \frac{HHV * \dot{n}_{H_2}}{I_{cell} * V_{cell}} \quad (5),$$

where $\triangle H_R^0$ [kJ/mol] is the standard formation enthalpy of water, P_{DC} [W] is the electrical power, HHV [kJ/mol] is the high heating value of hydrogen, $\dot{n}_{H_2}$ [mol/h] is the molar flow of hydrogen and I_{cell} [A] is the electrical cell current.

FIGURE 5 shows a schematic process flowsheet of an EL coupled with a MH tank as well as two secondary flash separators and control devices, likewise valves and an electrical trigger.

The proposed simulation setup allowed the PEM EL to be dynamically controlled when electrical energy is available, e.g., when there is a surplus of wind or photovoltaic power, and to produce hydrogen and oxygen from deionized water by electrochemical water splitting. The water input stream was connected to the anode side, where the oxidation process took place, and thus a mixture of gaseous oxygen and liquid residual water finally left the anode again. Meanwhile, at the cathode side, the electrochemical reduction reaction occurred, in which protons and a certain amount of water that had previously passed through the gas-liquid separation PEM were reduced to molecular hydrogen or released as liquid residual water. The obtained oxygen and hydrogen water mixtures of the anode and cathode, respectively, were separated into gaseous and liquid phases by the two flash separators.

The purified hydrogen was fed into the MH tank, which was cooled during the exothermic absorption process. In turn, the release of hydrogen from the MH tank was an endothermic process and was controlled by the provision of thermal energy via a heat transfer fluid.

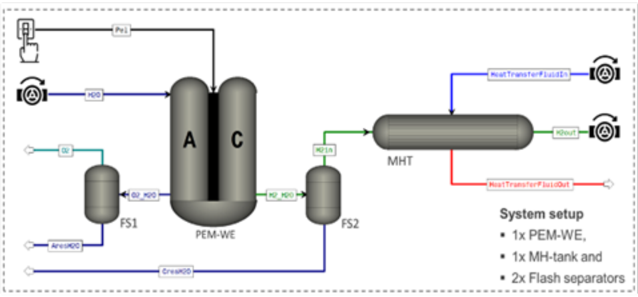


FIGURE 5: FLOWSHEET OF A PEM-EL COUPLED WITH A MH-TANK.

The MH tank simulation was based on the AB_2-alloy, Hydralloy C5, described above. The properties of the material employed in the simulations are described in TABLE I. The equilibrium pressure as a function of the temperature of the MH bed was calculated according to the van't Hoff law, as described in EQUATION (1). The intrinsic reaction kinetic was based on EQUATION (2). The thermal properties are based on a lumped effective thermal conductivity of the inner part of the tank and an assumed equidistant spatial distribution.

2) FC-MH-storage coupling

A 0D model for the PEM FC was implemented in Matlab/Simulink/Simscape (version R2021a). The model was based on the working principle of a PEM FC governed by redox reactions where hydrogen and oxygen are combined to produce water and heat (Q) as a by-product, and electrical power (P_{el}) as the main product. In this way, the electrical power and heat generation are connected. EQUATION 6 describes the whole process:

$$2H_2 + O_2 \rightarrow 2H_2O + P_{el} + Q \quad (6),$$

For the determination of the fuel cell output voltage (V_{fc}), the electrical model takes into consideration the thermodynamic output voltage (E) minus the activation and ohmic losses ($R_{ohm} \cdot i_{fc}$) from the fuel cell by applying EQUATION 7 [23]:

$$V_{fc} = E - R_{ohm} \cdot i_{fc} \quad (7),$$

The general assumptions of the developed model are: 1. mass transportation losses are neglected, 2. the temperature in the stack is maintained equal to the cathode and anode temperature and 3. humidity levels are kept suitable for any load.

The generated heat can be used for the coupling with the MH-storage tank since the hydrogen desorption is an endothermic reaction, FIGURE 6 shows a conceptual diagram of the PEM FC and MH tank coupling.

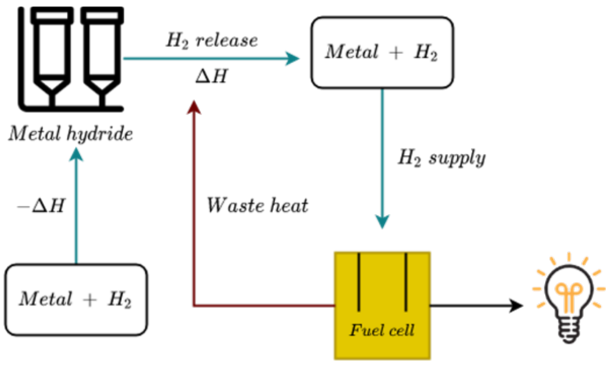


FIGURE 6: DIAGRAM SHOWING A BASIC PEM FC-MH COUPLING CONCEPT.

III. RESULTS AND DISCUSSION

In this section, the strategies to assemble the SET-Unit are described and developed. In the frame of the development of the project, recent results from ongoing tasks are shown. Furthermore, the prospects and next steps to reach the goals of the project are discussed.

A. Development and design of metal-hydride (MH) based systems

MH-based systems are the key technology for the development of the SET-Unit concept. The core of the MH systems is the hydride-forming material, M, which interacts with hydrogen by forming the hydride compound as described in EQUATION 8:

$$M + xH_2 \leftrightharpoons MH_{2x} + Q_{reaction} \quad (8),$$

As seen, the hydrogen absorption is exothermic and the hydrogen release is endothermic. For the proposed application of MH-storage and compression systems, interstitial hydrides, so-called room temperature hydrides, are the most suitable ones due to volumetric capacity, pressure and temperature range for hydrogen absorption-desorption and ease of handling. The interstitial hydrides absorb hydrogen by allocating it into the interstitial sites of the crystal structure of the hydride-forming material. Such interstitial hydrides are formed from alloys composed of different metal elements, such as Ti, Cr, Zr, Fe, Al, etc. There is a big variety of hydride-forming alloys which cover a wide range of pressures under mild temperature conditions. For the case of the project, the selected hydride forming alloy can cover operative temperature and pressure range between 20 and 150 ºC, and between 1 and 350 bar, respectively, gravimetric capacities between 1 and 3 wt% volumetric capacities (> 50 kg H_2/ m^3), ease of handling, and scale-up availability [7, 24]. Such room temperature hydrides allow the compact storage of hydrogen in a solid state under mild temperature and pressure conditions and the temperature-driven compression of hydrogen without the need for any mechanical process.

In this section, the development and design of MH-storage and MH-compressor systems for the SET-Unit for efficient solid-state hydrogen storage and compression are discussed.

1) Metal-hydride storage

1.1 Hydride forming alloy for large-scale application: characterization and improvement

The metal alloy Hydralloy C5 is utilized as a solid-state hydrogen storage material for this project because of the suitable thermodynamic stability and hydrogen gravimetric and volumetric capacity. This hydride-forming alloy can absorb hydrogen delivered from an electrolyzer in the range of pressure between 30 and 40 bar at room temperature (around 20 ºC). Hydralloy C5 further has the advantage of uncomplicated handling (stable in ambient conditions), fast activation process, and reasonable kinetic behavior. The operative gravimetric hydrogen capacity of Hydralloy is between 1.0 and 1.2 wt%, while the volumetric hydrogen capacity is between 50 and 60 kg H_2/m^3. FIGURE 7 shows that the maximum capacity of Hydralloy C5 is reached after 3 hydrogenation-dehydrogenation cycles. During hydrogen cycling, the material undergoes particle size reduction due to the swelling phenomenon. The swelling of the material is caused by the volumetric expansion of the metal lattice at the time to absorb hydrogen and allocate it to the lattice interstices (up to 30 % of volumetric expansion) [21, 25]. The metal alloy used as starting materials presented a size in the mm range (⩽ 4 mm). Due to the swelling phenomenon and considerable stress, the large millimetric particles of the metal alloy split to a size of about 20 µm regardless of the size of the starting material [26]. The MH in such powder form has a low effective thermal conductivity of about 1 $Wm^{-1}K^{-1}$ [17], which leads to low thermal diffusivity upon hydrogenation. This results in the formation of hot spots which slows down the kinetic performance owing to the increase of the equilibrium pressure and subsequent driving force reduction (difference between operative and equilibrium pressure).

The addition of expanded natural graphite (ENG) and pressing the metal alloy into pellets have been already shown to be effective approaches for improving heat conductivity [27]. This approach can be however only scaled up to a certain degree and needs additional experimental effort to find the optimum practical conditions for the formation of the pellets. It was, however, possible to improve the heat conductivity by simply mixing the Hydralloy C5 with 10wt% of ENG (see FIGURE 7). The peak temperature could be decreased from about 59 °C for pure Hydralloy C5 to about 56 °C in a Hydralloy C5-ENG mixture while retaining most of the hydrogen capacity (1.24 wt% vs. 1.15 wt%).

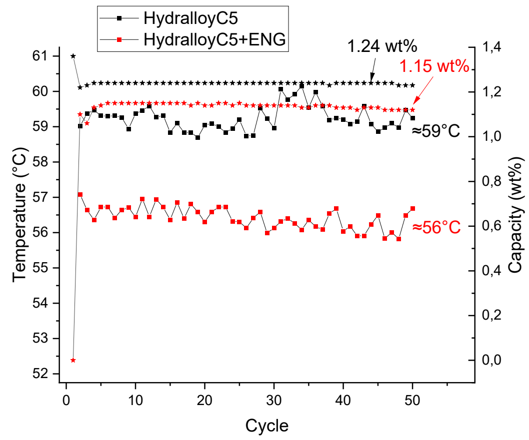


FIGURE 7: COMPARISON OF THE HYDROGEN CAPACITY (STAR-SHAPED DATA POINTS) AND THE MEASURED MAXIMUM TEMPERATURE DURING ABSORPTION (SQUARE-SHAPED DATA POINTS) FOR PURE HYDRALLOY C5 (BLACK) AND WITH A MIXTURE OF HYDRALLO C5 WITH 10 WT% OF ENG (EXPANDED NATURAL GRAPHITE, RED).

Another challenge of hydrogen storage in metal alloys is stress on the walls of the MH reservoir caused by the swelling upon hydrogenation. Such stress is increased by the decrepitation of the material during cycling, which leads to the compaction of the metal alloy powder at the bottom of the storage vessel. This expansion is in general compensated by leaving free space in the storage vessel, reducing the overall hydrogen gravimetric and volumetric capacity [21]. Experimental results have shown that the addition of ENG and compaction of the Hydralloy C5 powder can reduce the stress caused by swelling [27]. In other work [28], the effects of the swelling have been reduced by adding small amounts of Aerosil (0.2 wt%), which acts as a gliding agent and especially reduced the friction and compaction of the metal alloy powder at the bottom of the storage vessel [28]. In FIGURE 8, the experimental quantifications of the stress caused by the hydrogenation of Hydralloy C5 in a full sample holder with a compressed sample and reduced porosity. As seen, the pristine Hydralloy C5 causes excessive stress after a few cycles. Adding ENG reduces stress, and the combination of ENG and Aerosil further diminish such swelling effects. Mixing ENG and Aerosil with millimetric Hydralloy C5 material represents a scalable approach for increasing the degree of filling of hydrogen vessels based on MH [29].

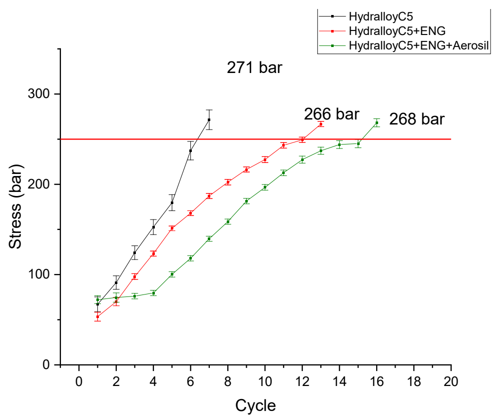


FIGURE 8: COMPARISON OF THE MEASURED STRESS TO THE WALL OF THE REACTION VESSEL DURING CYCLING. FOR THESE EXPERIMENTS, THE METAL ALLOY WAS FURTHER COMPRESSED IN THE SAMPLE HOLDER, TO

REACH THE CRITICAL LIMIT OF <40% POROSITY [21]. THE EXPERIMENTS HAVE BEEN STOPPED, AFTER REACHING THE ELASTIC DEFORMATION LIMIT (250 BAR). IN COMPARISON TO PURE HYDALLOY C5 (BLACK, 6 CYCLES), HYDRALLOY C5 + ENG MIXTURE (RED; 13 CYCLES), AND HYDRALLOY C5 + ENG + AEROSIL (GREEN; 16 CYCLES).

1.2 *MH-storage vessel design*

The MH-storage system is designed mainly to supply the needed amount of hydrogen for a specific application. To take decisions about the MH-storage reservoir design, a 2D digital model has been developed to investigate the impact of different design parameters applying FEM [30]. The cross-section of the cylindrical MH-storage reservoir with different numbers of fins (0, 4, 8, 12, 16) and for the endothermic dehydrogenation process has been assessed. For the sake of clarity and conciseness, the results obtained from the tank without fins and with 16 fins are here shown. FIGURE 9 shows the temperature distribution inside the storage vessel at different times for the configurations mentioned above.

For the case of the vessel without fins and at 600 seconds (FIGURE 9A), it can be seen that the temperature of the hydride bed close to the wall increases. However, the temperature of the hydride bed at the center of the tank does not appreciably increase. The design with 16 fins (FIGURE 9B) shows that also mostly the shell is heated up, but in this case, the temperature inside the shell is lower than the tank without fins and the fins themselves are heated up slightly. Here, it can also be seen, that only the temperature of the hydride close to the shell or close to the fins is slightly higher than in the center of that tank. This behavior is expected because the fins have far higher thermal conductivity than the metal hydride. The temperature of the shell itself is lower in the fin design because the energy is transferred faster into the center of the vessel by means of fins.

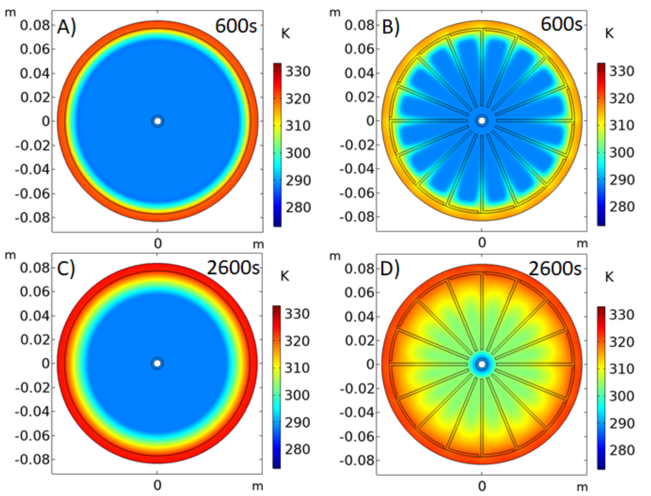


FIGURE 9: TEMPERATURE DISTRIBUTION INSIDE THE TANK VESSEL WITHOUT FINS (A AND C) AND WITH 16 FINS (B AND D) AT 600 S (A AND B) AND 2600 S (C AND D).

After 2600 s, it can be seen that the design without fins is still mostly cold inside the central part of the hydride bed (FIGURE 9C). Only the hydride mass closer to the shell has been heated up. It is also noticed that the temperature drops significantly inside the hydride bed, while the shell is at the same temperature as the heating fluid. This is due to the low effective thermal conductivity of the metal hydride, which results in an ineffective heat diffusivity inside the MH-vessel. On the contrary, in the design with 16 fins after 2600 s (FIGURE 9D), the whole hydride bed is mostly heated. Hence, the temperature gradient is much lower than the design without fins. Owing to the larger thermal conductivity of the aluminum fins and the effective contact with the MH bed resulting in enhanced effective thermal diffusivity, the internal heat management of the MH-hydrogen vessel is notably improved [31]. These results show that the implementation of fins as a strategy to tackle the poor heat exchange of the MH-bed is a proper approach that leads to a more effective response of the MH-storage vessel at the time to provide hydrogen to a fuel cell device, among other practical applications.

1.3 *MH-storage system development*

The development of the MH-storage system is mainly based on the hydrogen demand from the FC and the coupling with the MH-compressor, as well as the heat exchange management coupling, as depicted in FIGURE 2. As shown in FIGURE 7 and FIGURE 8, the selected room temperature material (Hydralloy C5) presents a capacity of around 1.1-1.2 wt%, swelling issues, and also poor thermal conductivity. The last issue related to internal thermal management of the MH-vessel has been addressed by implementing internal aluminum fins as shown in FIGURE 9. For supplying hydrogen to the planned lab-scale of 10 kWel and the scale-up to a 50 kWel fuel cell, a modular MH-storage system with a total capacity of 10 kg is developed. As seen in FIGURE 10, the system consists of a modular design with 5 MH-storage units containing 4 MH-storage tanks per unit. The whole system can be operated under different dynamic requirements by managing the heat in the units. Schematically, it is proposed to have different numbers of heat exchangers, so that the dynamic response of the system can be coupled with the dynamic of the whole SET-Unit. The hydrogen inlet and outlet lines coming from the electrolyzer and going to the FC or MH-compressors are independently connected by a three-way valve. The connection to the hydrogen lines allows for the charge and discharge of each tank, and even in the configuration with two and four heat exchangers, it is possible to charge and discharge tanks at the same time. The primary heat exchange system provides the cooling source for the hydrogenation process, while the dehydrogenation process is performed by using the waste heat from other devices such as the FC. The proposed configuration makes it possible to connect the MH-storage system with flexibility and to employ the system at different scales.

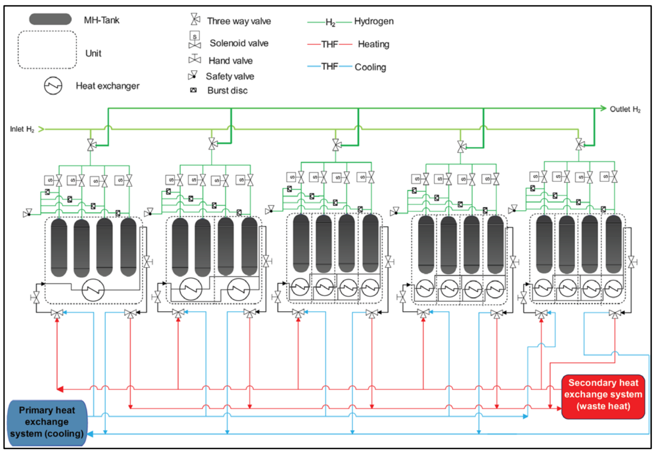


FIGURE 10: FLOW DIAGRAM OF THE MODULAR MH-STORAGE SYSTEM.

2) Metal-hydride compressor

2.1 Hydride forming alloy for thermally driven compression: development and characterization

In the area of hydrogen compression, metal hydrides have several advantages over the mechanical compressors used nowadays. The absence of moving parts and simple design, coupled with the possible low cost energy source, make metal hydrides a candidate as for hydrogen compressors [32]. Usually, AB_2 type intermetallic are used for high-pressure hydrogen compression, where A stands for Ti/Zr and B stands for mixtures of other transition metals. Hydrogen fills the tetrahedral sites without changing the symmetry of the unit cell. In the frame of Digi-Hypro, a $TiCr_{1.9}$ AB_2 type alloy is investigated as a potential hydrogen compression material for a high-pressure step owing to the simplicity of such binary hydride forming material, high equilibrium pressures, and low cost of its components. However, in some works, it is argued that the hydrogen capacity, as well as the equilibrium pressure, can be increased by adding elements to the alloy, which is not as trivial and reproducible at a larger scale [33]. Determining the enthalpy and entropy values of the synthesized alloy is critical for metal hydride hydrogen compressor design. Obtaining these important parameters serves to determine at what pressure the alloy will absorb or release hydrogen at a given temperature. FIGURE 11A shows the temperature dependence of absorption and desorption plateau pressures of $TiCr_{1.9}$ alloy. For example, for the $TiCr_{1.9}$ composition to absorb hydrogen at room temperature, H_2 a pressure above 50 bar at a room temperature of 25 ºC is required. The absorbed sample can desorb hydrogen up to a pressure of about 350 bar H_2 when heated to 140 ºC. Therefore, P_{eq}-Temperature curves are very useful because they allow for determining the maximum pressure that the hydrogen compressor can reach under a certain temperature.

When a metal alloy absorbs hydrogen, its unit cell volume expands causing swelling [25]. Determining such volumetric increase is very important for tank design to prevent excessive stress on the internal tank shell. This volume expansion can be calculated by evaluating the diffraction patterns of as-synthesized and hydrogenated material. FIGURE 11B shows the diffraction patterns of the synthesized and hydrogenated samples.

Phase analyses using the Rietveld approach show that the synthesized $TiCr_{1.9}$ has a C14 Laves phase and a calculated unit cell volume of 167.5 Å^3 (cell parameters, a: 4.92 Å, c:7.98 Å). Hydrogenation of the sample causes a shift in the diffraction peaks to lower angles due to the increase in the lattice parameters (FIGURE 11B). The unit cell volume of the hydrogenated phase was calculated as 193.1 Å^3 (cell parameters, a: 5.13 Å, c:8.45 Å). This means that there is a 15.3 % increase in the unit cell volume of the sample with hydrogen uptake.

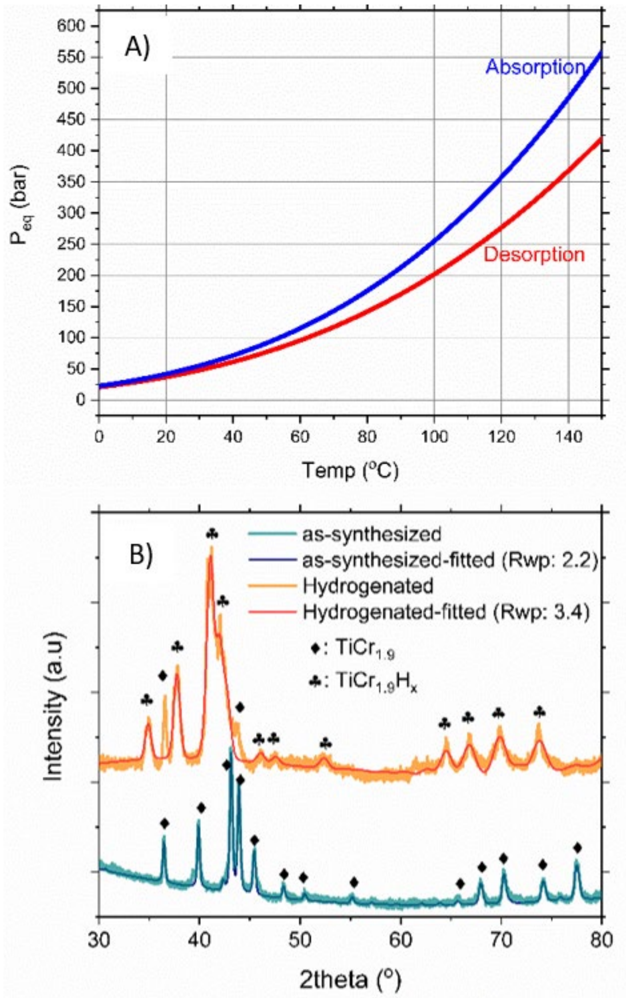


FIGURE 11: A) DEPENDENCE OF ABSORPTION/DESORPTION PEq ON TEMPERATURE B) DIFFRACTION PATTERNS OF AS-SYNTHESIZED AND HYDROGENATED $TiCr_{1.9}$, AS WELL AS FITTED CURVES AFTER RIETVELD REFINEMENT. RWP (%) REPRESENTS THE FITTING GOODNESS.

2.2 MH-compressor vessel design

The compression process is a batch process where the pressure vessel and MH-bed are heated up and cooled down repeatedly. Thus, it is necessary to design the vessel considering two important factors. First, an efficient heat transfer to extract the heat released from the exothermal hydrogenation reaction and utilize it for different means. Second, a minimal mass of the pressure vessel shell, so that the energy required for heating up and cooling down is not excessive. Through simulating different configurations of the pressure vessel, a design with improved efficiency for the total compression process can be found.

The shape of the vessel has a strong influence on the heat transfer between the MH-bed, the hull of the vessel, and the external heat transfer fluid, which significantly influences the reaction kinetic behavior of the MH. Especially the diameter D and length L of the cylindrical shell of the compressor vessel and the resulting ratio L/D are important parameters influencing the heat transfer of the compressor. To ensure safety and take into account additional important engineering aspects like cost and manufacturability, during the design, the wall thickness is calculated by Barlow's formula as a function of the diameter [34]

Different diameters and lengths of vessels are investigated. The main challenge in simulating the MH-compressor lies in modeling the different transient compression steps and the physical coupling between the two stages since two reactions, the desorption of hydrogen in the first stage, and the absorption into the second stage take place simultaneously.

Some preliminary results for the pressure during a complete compression cycle for an unoptimized compressor can be seen in FIGURE 12. This unoptimized compressor configuration has an inner diameter of 4 mm and is filled with 5 kg of Hydroalloy C5 and 4 kg of AB_2 material. The target pressure of 200 bar can be reached at a temperature of 100 ºC. The time for the complete compression process is around 16 h, which represents a very long time and is a matter of further optimization.

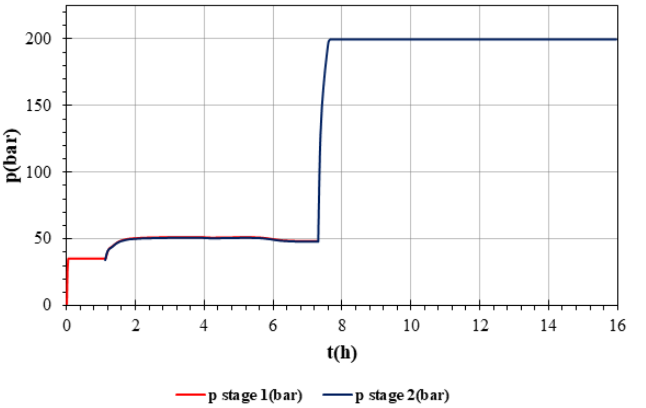


FIGURE 12: PRESSURE DURING COMPLETE COMPRESSION CYCLE IN FEM-SIMULATION OF MH-COMPRESSOR AT AN HTF TEMPERATURE OF 100 °C.

One of the first approaches to improve the performance of the MH-compressor is the improvement of the internal heat management as exposed in FIGURE 9 for the MH- storage system. Moreover, there are also strategies to be implemented for the hydride-forming alloy such as the compaction of the powder [35] or the improvement of the characteristics of the material as described in FIGURE 7 and FIGURE 8.

As part of ongoing work, it is planned to perform the design of a two-stage MH-compressor by employing low and high-pressure hydride forming alloys with more appropriate characteristics such as higher equilibrium pressures at lower temperatures, particularly for the second stage, as shown in FIGURE 11A for the case of $TiCr_{1.9}$, as well as faster kinetic behavior. Two alloys like the ones described in TABLE I will be used. The potential selected alloys were chosen based on the range of temperature and resulting equilibrium pressures and kinetic characteristics. These are Hydralloy C5 and $MmNi_{5-x}Fe_x$ for the low-pressure stage and $TiCr_y$-based alloys for the high-pressure stage [21]. Such alloys can be produced in large amounts (~ 30 kg), which represents an intermediate scale for the development of 2-stage MH-compressors. To design the pressure vessel, FEM elements simulations are a powerful tool to predict and improve the hydrogen compression performance of a proposed design.

2.3 MH-compressor system development

The metal hydride compressor serves the general purpose to raise the pressure level of hydrogen from the SET-Unit to connect to vehicles equipped with compressed gaseous hydrogen storage. The performance requirements of such compressors are focused on two main premises. On the one hand, the integration of a 2-stage MH-compressor into the SET-Unit defines the compressor size, hydrogen throughput, and achievable pressure, as well as operating modes, mainly by the availability of hydrogen and energy in the system. On the other hand, the compressor design aims to fulfill the refueling process in terms of pressure level, amount of hydrogen, and refueling frequency.

The compressor will comprise two stages with an AB_5 or AB_2 material ($MmNi_{5-x}Fe_x$ or Hydralloy C5) in the first stage to increase the pressure from the metal hydride storage or directly from the electrolyzer to an intermediate level which is then further increased by an AB2 material ($TiCr_y$-based) in the second stage. The final pressure level is aimed to be suitable for the refueling of storage systems at the 350 bar pressure level, which is the common technology for buses and heavy-duty trucks at the time [36, 37]. However, the achievable pressure level will depend on the characteristics of the material still to be delivered. The general design decision was mainly based on the commercial availability of the hydride forming alloys, the expected temperature levels in the SET-Unit, and the reduced complexity as well as efficiency benefits of a two-stage design compared to three or more stages.

FIGURE 13 shows the working principle of a two-stage metal hydride compressor in the batch process. Each stage comprises a cylindrical vessel containing the hydride forming material and a cooling/heating jacket guiding the heat transfer fluid around it. The setup allows to periodically cool and heat the material and therefore drive the absorption and desorption at a higher pressure, respectively.

The cylinder and heat jacket are one of the proposed potential designs to handle the mass and heat transfer in the compressor. To drive forward the compressor system design, the current work comprises a review of the vessel designs proposed in the literature [21, 38, 39] and transferring them into simple steady-state models. From the heat and mass balances in these models, the amounts of material and energy are derived in the scale that fits the size of the other components of the SET-Unit.

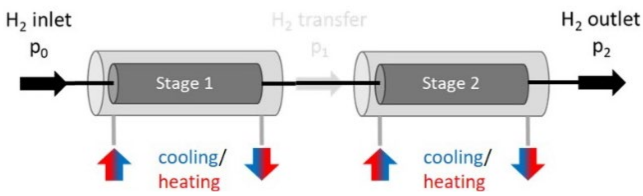


FIGURE 13: FUNCTIONAL PRINCIPLE OF A TWO-STAGE METAL HYDRIDE COMPRESSOR.

As seen in FIGURE 14, the two-stage compressor in continuous operation can be described in a flow diagram showing the main components: the vessels with heat exchangers, piping, and valves. In FIGURE 14, the upper half of the diagram forms one unit, and the lower half forms the second. Both units are alternately cooled or heated by a heat transfer fluid (HTF). Unit 1 is cooled by opening the HTF inlet valve V1.4 and drain valve V1.6. The hydrogen flow is guided by opening V1.1 and closing V1.2 to drive the absorption process in stage 1. Also, stage 2 is absorbing hydrogen coming from the first stage of the second unit. This is possible because unit 2 is heated and thus desorbs hydrogen. After that, the heating/cooling of the two units is inversed and the hydrogen flow is guided by valves V1.1-3 and V2.1-3 accordingly.

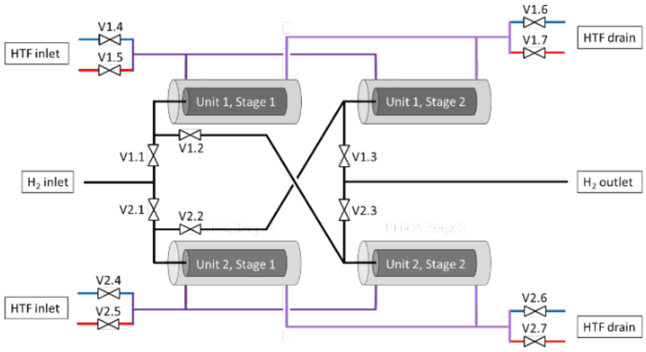


FIGURE 14: FLOW DIAGRAM OF A POTENTIAL TWO-STAGE COMPRESSOR DESIGN FOR CONTINUOUS OPERATION.

Furthermore, the requirements for the coupling with the mobility sector are a matter of ongoing analysis by reviewing updated literature and roadmaps for future hydrogen refueling of long-haul trucks. Published works such as [36, 37, 40, 41, 42] are part of the analysis and represent the technology state of the art. Performance indicators have been identified and compared to the SET-Unit in the intermediate scale (50 kWel). Among the indicators used for comparison, the average flow rate of hydrogen during a filling event stood out as the most challenging for the metal hydride compressor as high amounts of metal hydride material and heating/cooling power would be required. Therefore, different MH-compressor designs and their combination with buffer pressure tanks, allowing for a more time-independent and continuous operation, feasibility, and manufacturability are part of the ongoing analysis to find the optimum design.

B. *Membrane Technology for Hydrogen Processing*

A techno-economically viable separation process to extract hydrogen from NG blends underpins the overall feasibility of a trilateral connection between the power, gas, and mobility sectors. Due to its diverse end consumers, hydrogen should be purified to different levels of quality. In comparison to the stationary applications, the requirements specified in the ISO 14687-2 standards for vehicles' PEM fuel cells are significantly more stringent and challenging due to the very low limits of contamination to be achieved. Therefore, our focus is on modeling a separation process customized for the latter applications. A so-called hybrid process taking advantage of both membrane and pressure swing adsorption (PSA) techniques are considered the most promising configuration. In this process scheme, the bulk separation of hydrogen is accomplished in the membrane unit while the following PSA module enhances the final product quality. The process flowsheet as depicted in FIGURE 15 has been developed using Aspen Custom Modeler V12 (ACM) and Aspen Adsorption V12. An envelope-type Matrimid membrane module, which is modeled in ACM, was combined with a 4-bed PSA system. Depending on the downstream applications, the PSA separation can be equipped with two or three layers of adsorbents. The conservation equations of mass, momentum, and energy are simultaneously solved using the finite difference method combined with numerical integration.

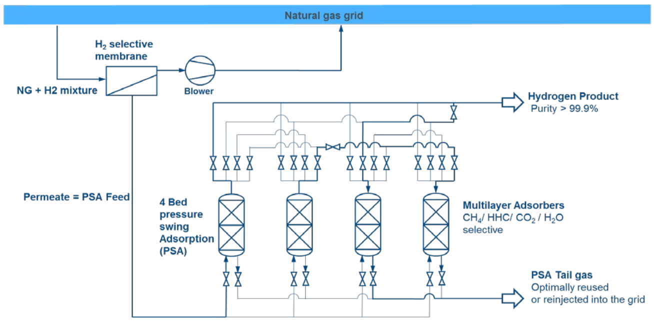


FIGURE 15: A HYBRID SEPARATION PROCESS FOR HYDROGEN RECOVERY AND PURIFICATION.

C. *System Integration*

Process and system simulations with the combination of system control and regulation strategies are essential tools for the analysis of sub-systems (bottom-up analysis) and the whole Set–Box (top-down analysis). These tools are also applied for cost-efficient designs and scale-up validations, especially for new conversion and storage energy systems. Different from the 2D or 3D simulations performed applying finite element modeling, 0D models are generally not focused on a single device but are used to model entire systems with multiple interconnected devices [43]. By incorporating the collected information from the spatial finite element simulations and experimentally determined material data, accurate and computationally powerful 0D models can be created. In this section, the first approaches of 0D models for the PEM EL-MH tank and PEM FC-MH tank subsystems and the control for the whole SET-Unit are discussed.

1) *PEM EL-MH system*

FIGURE 16 illustrates the polarization curve of the PEM EL model including the activation, concentration, and ohmic overpotentials as well as the cell efficiency calculated according to Equation (5).

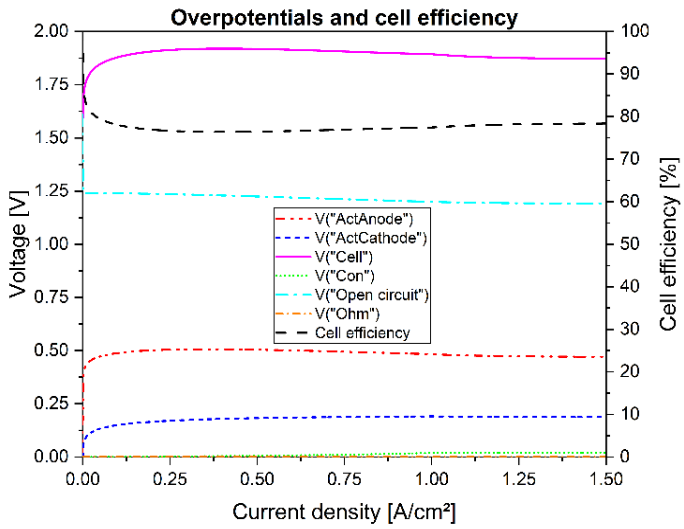


FIGURE 16: SIMULATED OVERPOTENTIALS AND CELL EFFICIENCY

Since the EL operating temperature and pressure have a major impact on the occurring cell voltage, investigations on the optimal process parameters e.g., by the usage of a dynamic digital twin are of great importance. A cold start was simulated at an ambient temperature of 20 °C, which then increased to the final operating temperature of 80 °C and a current density of 1.5 A/cm². The applied electrical power was ramped at 1 kWel/min, which is one of the system boundary conditions to meet the requirements for a fast system response time. The PEM EL was modeled with a nominal electrical power of 10 kWel with a hydrogen output pressure of 38 bar and, since a hydrogen mass flow of 170 g/h was defined, operated with 8.5 kWel. It is noticeable that the cell voltage drops slightly or rather the cell efficiency increases, although the current density is increased. The reason for this phenomenon is, on the one hand, the temperature increases due to the waste heat generated in the EL and, on the other hand, the pressure and temperature dependence of the electrocatalytic water splitting. According to Arrhenius reaction kinetics, in general, the higher the operating temperature, the better the electrode kinetics and the lower the thermodynamic energy requirement. However, since the membrane must be fully hydrated to avoid degradation problems, the practical usable operating temperature of Nafion-based PEM EL is limited to the boiling point of water or rather the dehydration of the membrane [22].

The concept of a MH tank as a solid-state hydrogen storage system and its design and boundary conditions were previously described: TABLE I and FIGURE 3. This 0D MH tank model simulated a capacity of 695 g of absorbed hydrogen by using about 62.5 kg of room temperature AB2-alloy, Hydralloy C5. The mass balances of the AB2-alloy, MH, and absorbed hydrogen of the simulated absorption are presented in FIGURE 17.

The absorption process lasted about 250 min with the hydrogen mass flow rate of 170 g/h and a pressure of 38 bar provided by the PEM EL. Assuming a convective heat coefficient of 500 W/(m²*K) for the outer tank shell and a coolant flow of 10 NL/min with a temperature of 20 °C, the tank reached a final temperature of about 25.5 °C. In contrast, the desorption process was simulated at a hydrogen output mass flow of 670 g/h and a defined minimum pressure of 5 bar with a duration of about 60 min. The flow rate of the heat transfer fluid was increased to 60 L/min and applied at a higher temperature of 60 °C. A tank minimum temperature of 15 °C was obtained during the desorption.

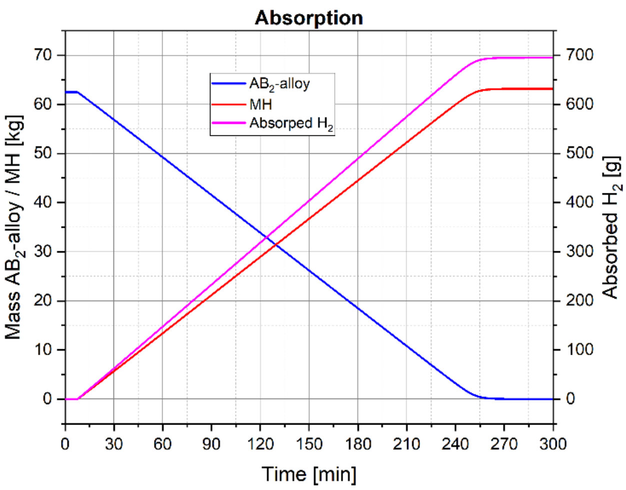


FIGURE 17: MASSES VS. TIME DURING THE ABSORPTION PROCESS [44].

2) PEM FC-MH system

A FC is an electrochemical device that converts chemical energy into electrical energy, as described above. Among the different types of fuel cells, PEM FC is the most common one due to its simplicity [45]. PEM FCs are now used mainly for different applications due to their high-power density; low operating temperature and quick start due to their operation to near ambient temperature [5].

For our laboratory scale, a water-cooled PEM FC stack with a rated power of 5 kWel from the company Power Cellution is going to be installed [46]. The stack is included in a so-called V5 system additionally having power, fuel, and oxidant control and regulation. The integrated cooling subsystem manages the cooling fluid and produces heat that can be used in our heat management system for coupling it with our metal hydride storage system.

One way of characterizing a FC and analyzing its performance is by obtaining the polarization curve. The polarization curve shows the electrical behavior of the fuel cell and is plotted using the voltage output of the fuel cell in a specific current demand range. According to the electrical losses of the fuel cell, three regions can be described: the activation region, the ohmic region, and the mass transport region. It is desired that the fuel cell be operated in the ohmic region since it is here where it is the most stable. In the activation region, the redox reactions are not happening fast enough and in the mass transport region, the power demand is faster than the reaction rate. FIGURE 18 shows a good agreement with a correlation factor of 0.9 between the modeled and the experimental device polarization for one cell. The simulated curve is based on the electrochemical model described by EQUATION (6) and EQUATION (7) [23]. Both polarization curves are not taking into consideration the mass transport region. The operational range can be defined as a current between 22 A and 105 A where the rated power is reached.

For the efficient coupling of the fuel cell with the MH-storage tank, the model has been improved to first account for the hydrogen flow and thermal interaction between MH-Tank and PEM FC in a steady state. It is also part of the ongoing work modeling the dynamic state under different power demand scenarios to analyze the performance and limits of the PEM FC-MH system. The heat produced by the FC and the temperature in such dynamic power demand scenarios can be calculated by employing the thermal model implemented in Matlab to obtain insights into the regulation and control of heat management.

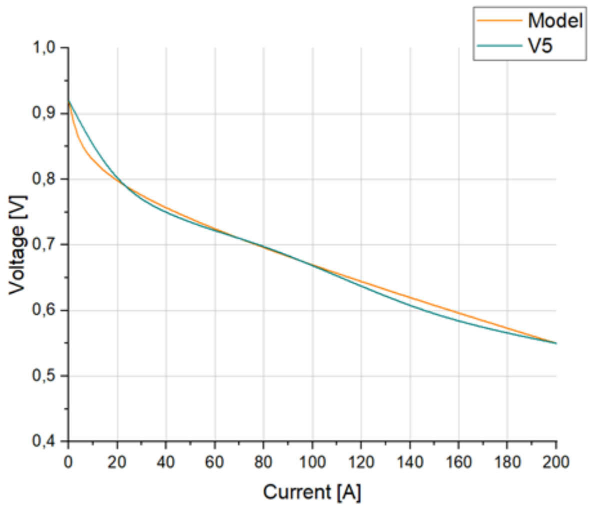


FIGURE 18: COMPARIZATION BETWEEN THE POLARIZATION CURVE FOR THE V5 SYSTEM OF POWER CELLUTION AND THE MATLAB ELECTRICAL MODEL WITH FITTING GOODNESS OF 0.9.

3) *Control and regulation approaches*

The SET-Unit involves the coupling of several devices and systems such as MH-storage, compressor tanks, FC, EL, and membrane gas separation, as shown in FIGURE 1. Each device presents its dynamic response, and therefore a proper control and regulation strategy is necessary to design an efficient coupled system. One of the most important parameters to consider at the time to develop the control and regulation approach for the SET-Unit is the adequate management of the heat. Hydrogen flow and thus the efficiency of the whole system highly depends on heat exchange management. The efficient utilization of the waste heat for hydrogen release as well as cooling demand for charging the MH tanks have to be considered to reduce extensive efficiency losses by including additional energy supply.

As an example of heat coupling and management, in the TecBia project waste heat from a PEM FC was utilized to release hydrogen from 48 MH-tanks [47]. TecBia was built for a maritime onboard power generation of 140 kW. To avoid heat peaks in the FC while switching power levels, seawater in the range of temperatures between 15 and 25 °C was used and the control strategy was carefully analyzed. Another example, but related to stationary applications, is the case of a project using exhaust heat recovery in Japan [48]. The system was designed with the economical objective to generate and store hydrogen during the night and reverse the process during day time since the electricity is cheaper by 50 % at night. Such a system can store 100 Nm^3 of hydrogen. The mechanism of the exhaust heat recovery is not reported and represents one of the key factors for the efficiency of the system.

The projects mentioned above can run in batch mode, which is per se quite challenging. A step forward is the design of such integrated systems to operate in continuous mode. For such purpose, the different components could be controlled independently enabling the possibility to switch between batch and continuous working mode. An operative continuous mode would involve a highly dynamic behavior of the whole system.

FIGURE 19 shows the energy flows to be controlled for the SET-Unit operation. Several components can act either as a heat energy source or sink depending on the configuration and operation mode of the system. Assuming the direct MH-storage and the FC connection, the combination of heat supply from FC and the demand for desorption is sufficient to ensure hydrogen flow to generate electrical power. Considering a third unit, such as MH-compressor requires energy for hydrogen release at the same time, such energy demand can be compensated by a surplus of heat delivered during the absorption of hydrogen in the MH-storage tank connected to the EL.

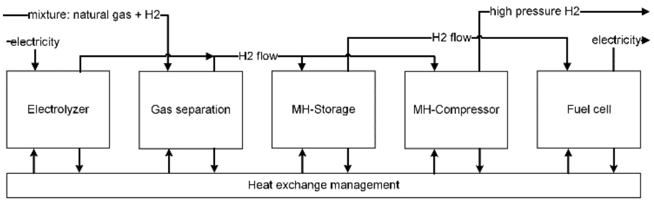


FIGURE 19: SET-Unit SCHEME ENERGY FLOW TO BE CONTROLLED.

To avoid a lack of energy, the operating conditions of the whole system can either be fixed to batch mode, limited to the dynamic operation, or an intermediate mode operation can be implemented. To enable a flexible utilization of the system, a novel complex control strategy must be developed taking into consideration the critical parameters and the operation modes of the whole system.

IV. SUMMARY AND PROSPECTS

The Digi-HyPro project aims to develop a modular system, called Smart-Energy-Transform-Box (SET-Unit) to supply decentralized clean energy demands. The SET-Unit serves to optimize the connections between renewable sources and the current power and gas grid demand. This multidisciplinary project involves the engineering of a complex coupled system and the generation of digital twins at different levels, i.e., component (EL, FC, MH-based devices, and gas separation process), subsystem (EL-MH-based devices, FC-MH-storage, etc.), and whole system (SET-Unit) level. Experimental setups of the SET-Unit are developed at the kW range scale. Bottom-up and top-down approaches are applied to design the SET-Unit system.

As part of the bottom-up approach, for the case of the 10 kWel scale, commercial EL and FC devices have been procured and their responses have been characterized based on SIM 0D model simulations. Furthermore, the coupling with the MH-storage system has been tested. Room temperature hydrides have been selected as the core materials for MH-storage and MH-compressor systems because of their adequate storage properties and suitable temperature and pressure conditions for coupling with the FC and EL. A modular MH-storage system with a capacity of 10 kg stored in an AB2 alloy is under development, and its design is based on FEM and the characterization and improvement of the hydride-forming alloy material. Aiming to connect the set box with the mobility sector, a two-stage MH-compression is designed based on FEM and system analyses. The selected materials for the low- and high-pressure stages are AB5 and AB2 room temperature hydrides, respectively. The top-down approach is also part of the investigations and has as aim to investigate and optimize control and regulation strategies for the SET-Unit.

The combination of simulations, experimental setup developments, and the analysis of the whole SET-Unit will allow obtaining information about the responses of the system and its range of applications.

ACKNOWLEDGMENTS

Funding by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr – is gratefully acknowledged [project: Digi-HyPro].

REFERENCES

[1] Y. Sugiawan, S. Managi, New evidence of energy-growth nexus from inclusive wealth, Renewable and Sustainable Energy Reviews, Volume 103, 2019, Pg. 40-48, https://doi.org/10.1016/j.rser.2018.12.044

[2] Our World In Data, https://ourworldindata.org/fossil-fuels#global-fossil-fuel-consumption (accessed September 05, 2022).

[3] NASA Earth observatory, https://earthobservatory.nasa.gov/features/GlobalWarming/page2.php (accessed September 05, 2022).

[4] I.E. Agency, Global Energy Review 2021 - Assessing the effects of economic recoveries on global energy demand and CO2 emissions in 2021 Global Energy, (2021), https://iea.blob.core.windows.net/assets/d0031107-401d-4a2f-a48b-9eed19457335/GlobalEnergyReview2021.pdf (accessed September 05, 2022).

[5] T. Egeland-Eriksen, A. Hajizadeh, S. Sartori, Hydrogen-based systems for integration of renewable energy in power systems: Achievements and perspectives, Int. J. Hydrogen Energy. 46 (2021) 31963–31983. https://doi.org/10.1016/j.ijhydene.2021.06.218

[6] I.A. Hassan, H.S. Ramadan, M.A. Saleh, D. Hissel, Hydrogen storage technologies for stationary and mobile applications: Review, analysis, and perspectives, Renew. Sustain. Energy Rev. 149 (2021) 111311. https://doi.org/10.1016/J.RSER.2021.111311.

[7] J. Bellosta von Colbe, J.R. Ares, J. Barale, M. Baricco, C. Buckley, G. Capurso, N. Gallandat, D.M. Grant, M.N. Guzik, I. Jacob, E.H. Jensen, T. Jensen, J. Jepsen, T. Klassen, M. V. Lototskyy, K. Manickam, A. Montone, J. Puszkiel, S. Sartori, D.A. Sheppard, A. Stuart, G. Walker, C.J. Webb, H. Yang, V. Yartys, A. Züttel, M. Dornheim, Application of hydrides in hydrogen storage and compression: Achievements, outlook and perspectives, Int. J. Hydrogen Energy. 44 (2019) 7780–7808. https://doi.org/10.1016/j.ijhydene.2019.01.104

[8] W. Liemberger, M. Groß, M. Miltner, M. Harase, Experimental analysis of membrane and pressure swing adsorption (PSA) for the hydrogen separation from natural gas, Journal of Cleaner Production (2017). https://doi.org/10.1016/j.jclepro.2017.08.012

[9] Supporting decarbonization by pipelining H2 to the point of use https://www.linde-engineering.com/en/images/H2Tech-Article-Q4-issue-2021_tcm19-647879.pdf

[10] H. M. Rietveld, A profile refinement method for nuclear and magnetic structures, J. Appl. Crystallogr., vol. 2, pp. 65–71, 1968. https://doi.org/10.1107/S0021889869006558

[11] L. Lutterotti, Total pattern fitting for the combined size-strain-stress-texture determination in thin film diffraction, Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, 268 (2010) 334–340. https://doi.org/10.1016/j.nimb.2009.09.053

[12] R. Schulz, S. Boily, and J. Huot, Equipment for gas titration and cycling of an adsorbend material E, CA 2207149, 1997.

[13] J.A. Puszkiel, Tailoring the Kinetic Behavior of Hydride Forming Materials for Hydrogen Storage, Intech. i (2016) 13. https://www.intechopen.com/chapters/64686

[14] Capurso, G., Schiavo, B., Jepsen, J. et al. Development of a modular room-temperature hydride storage system for vehicular applications. Appl. Phys. A 122 (2016) 236. https://link.springer.com/article/10.1007/s00339-016-9771-x

[15] P. S. Krause, J. Warfsmann, E. Wienken, J. Jepsen, T. Klassen, J. Puszkiel, Book of abstract, DIGITAL DEVELOPMENT OF AN OPTIMIZED HEAT MANAGEMENT DESIGN FOR AN INTEGRATED SOLID-STATE H2-STORAGE RESERVOIR, page 85" Available: https://drive.google.com/file/d/10X1tZrIAAmJK7Aoj58QuyctCV_Qbw8LR/view [last visti 01.9.22]

[16] V.M. Skripnyuk, M. Ron, Evaluation of kinetics by utilizing the normalized pressure dependence method for the alloy Ti0.95Zr0.05Mn1.48V0.43Fe0.08Al0.01, J. Alloys Compd 293 –295 (1999) 385 –390

[17] S. Suda, Y. Komazaki, N. Kobayashi, Effective thermal conductivity of metal hydride beds. Journal of the Less Common Metals 1983, 89 (2), 317–324. DOI: 10.1016/0022-5088(83)90340-5.

[18] J. Puszkiel, J.M. Bellosta von Colbe, J. Jepsen, S.V. Mitrokhin, E., Movlaev, V. Verbetsky, T. Klassen, Designing an AB2-type alloy (TIZr-CrMNMO) for the hybrid hydrogen storage concept. Energies, 13(11), 2751, 2020. https://doi.org/10.3390/en13112751

[19] J.A. Puszkiel, J. Bellosta von Colbe, J. Jepsen, V.N. Verbetsky, S.V. Mitrokhin, E.A. Movlaev, T. Klassen, M. Dornheim, Design of an optimized hybrid hydrogen storage reservoir with high capacity. MH2018. Guangzhou, China, 2018.

[20] O. Gillia, Hydride breathing and its consequence on stresses applied to containers: a review. Int. J. of Hydrogen Energy, 46(72) (2021) 35594-35640. https://doi.org/10.1016/j.ijhydene.2021.07.082

[21] M.V. Lototskyy, V.A. Yartys, B. Pollet, R.C. Bowman: Metal hydride hydrogen compressors: a review. International journal of hydrogen energy, 39(11) (2014) 5818-5851. https://doi.org/10.1016/j.ijhydene.2014.01.158

[22] D. Bessarabov et al., PEM Electrolysis for Hydrogen Production, Florida: CRC Press, 2017. https://doi.org/10.1201/b19096

[23] N.M. Souleman, O. Tremblay, L.A. Dessaint, A generic fuel cell model for the simulation of fuel cell power systems. 2009 IEEE Power and Energy Society General Meeting, PES '09, 1722–1729. https://doi.org/10.1109/PES.2009.5275853

[24] A. Lys, J.O. Fadonougbo, M. Faisal, J.Y. Suh, Y.S. Lee, J.H. Shim, Y. Cho, Y. W. Enhancing the hydrogen storage properties of AxBy intermetallic compounds by partial substitution: a short review. Hydrogen, 1(1)(2020) 38-63. https://doi.org/10.3390/hydrogen1010004

[25] B. Charlas, O. Gillia, P. Doremus, D. Imbault, D. Experimental investigation of the swelling/shrinkage of a hydride bed in a cell during hydrogen absorption/desorption cycles. Int. J. of Hydrogen Energy 37 (21) (2021) 16031–16041. https://doi.org/10.1016/j.ijhydene.2012.07.091

[26] F. Qin, L.H. Guo, J.P. Chen, Y.J. Chen, Pulverization, expansion of La0.6Y0.4Ni4.8Mn0.2 during hydrogen absorption–desorption cycles and their influences in thin-wall reactors. Int. J. of Hydrogen Energy 33 (2) (2008) 709–717. https://doi.org/10.1016/j.ijhydene.2007.10.029

[27] C. Pohlmann, L. Röntzsch, F. Heubner, Weißgärber, T.; Kieback, B. Solid-state hydrogen storage in Hydralloy–graphite composites. J. of Power Sources 2013, 231 (Suppl. 2), 97–105. https://doi.org/10.1016/j.jpowsour.2012.12.044

[28] D.J. Cuscueta, N. Silin, M. Melnichuk, Stress reduction in a hydride container by the addition of a glidant agent. Int. J. of Hydrogen Energy 2020, 45 (51), 27452–27456. DOI: 10.1016/j.ijhydene.2020.07.020.

[29] J. Warfsmann; M. Passing, P.S. Krause, E. Wienken, J. Jepsen, T. Klassen, J.A. Puskiel, Easy Up-Scalable Approach to Improve the Properties of Metal-Alloys for Hydrogen Storage, In *23rd World Hydrogen Energy Conference (WHEC 2022)*, Istanbul 26-30 June 2022, Dincer, I., Colphan, C. O., Ezan, M. A., Eds.. ISBN: 978-625-00-0843-0. Available: https://drive.google.com/file/d/10X1tZrIAAmJK7Aoj58QuyctCV_Qbw8LR/view [accessed 05.9.22].

[30] P. S. Krause, J. Warfsmann, E. Wienken, J. Jepsen, T. Klassen, J. Puszkiel, Book of abstract, Digital development of an optimized heat management design for an integrated solid-state H_2-storage reservoir, In *23rd World Hydrogen Energy Conference (WHEC 2022)*, Istanbul 26-30 June 2022, Dincer, I., Colphan, C. O., Ezan, M. A., Eds.. ISBN: 978-625-00-0843-0. Available: https://drive.google.com/file/d/10X1tZrIAAmJK7Aoj58QuyctCV_Qbw8LR/view [accessed 05.9.22].

[31] A. Mahvash, R. Mane, P. Sharma. Heat transfer techniques in metal hydride hydrogen storage: A review. Int. J. of Hydrogen Energy 52 (2017): 30661-30682. https://doi.org/10.1016/j.ijhydene.2017.10.166

[32] M. Lototskyy and V. Linkov, Thermally driven hydrogen compression using metal hydrides, Int. J. Energy Res. 1–21 (2022). doi: 10.1002/er.8189.

[33] W. Jiang, C. He, X.-B. Yang, X. Xiao, L. Ouyang, and M. Zhu, Influence of element substitution on structural stability and hydrogen storage performance: A theoretical and experimental study on TiCr2-xMnx alloy, Renew. Energy 197 (2022) 564-573. doi: 10.1016/j.renene.2022.07.113.

[34] Verband der TÜV: AD 2000 Regelwerk. 13. Auflage. Berlin: Beuth (Beuth Praxis), 2021.

[35] J. K. Kim, I. S. Park, K.J. Kim, K. Gawlik, A hydrogen-compression system using porous metal hydride pellets of LaNi5-xAlx. Int. J. of hydrogen energy, 33(2) (2008) 870-877. https://doi.org/10.1016/j.ijhydene.2007.10.027

[36] H2 MOBILITY: Wasserstoffbetankung von Schwerlastfahrzeugen – die Optionen im Überblick. H2 MOBILITY Deutschland GmbH & Co. KG. Berlin, 2021. [Online]. Available: https://h2-mobility.de/wp-content/uploads/sites/2/2021/10/H2M_Ueberblick_BetankungsoptionenLNFSNF_TankRast_2021-10-21.pdf. accessed: September 05, 2022

[37] Y. Rulf, M. Baum, T. Zorn, A. Menzel, A. Rehberger: Fuel Cells Hydrogen Trucks. Heavy-Duty's High-Performance Green Solution. Study Summary. Hg. v. Fuel Cells and Hydrogen Joint Undertaking, Brüssel, 2020. [Online]. Available: https://www.fch.europa.eu/publications/study-fuel-cells-hydrogen-trucks. accessed: September 05, 2022

[38] B.P. Tarasov, B.S. Mikhail, Y.B. Yurii, P.V. Fursikov, M. B. Konstantin M.V. Lototskyy, Metal hydride hydrogen compressors for energy storage systems: layout features and results of long-term tests. In: J. Phys. Energy, 2020. https://iopscience.iop.org/article/10.1088/2515-7655/ab6465

[39] C. Yehui, Z. Xiangguo, X. Junfeng, K. Huaqin, The comprehensive review for the development of heat exchanger configuration design in metal hydride bed. Int. J. of Hydrogen Energy 47 (2022) 2461-2490. https://doi.org/10.1016/j.ijhydene.2021.10.172

[40] R. Peters, J. Breuer,M. Decker, T. Grube, M. Robinius, M. Samsun, C. Remzi, D. Stolten, Future Power Train Solutions for Long-Haul Trucks, Sustainability 13(4) (2021) 2225. https://doi.org/10.3390/su13042225

[41] P.K. Rose, F. Neumann, Hydrogen refueling station networks for heavy-duty vehicles in future power systems. P.K. Rose, F. Neumann, Hydrogen refueling station networks for heavy-duty vehicles in future

power systems. Transportation Research Part D: Transport and Environment D83 (2020) 102358. https://doi.org/10.1016/j.trd.2020.102358

[42] Sinding D., C. Hart, N. Quong, S. Karzel, P. Vyazmina, E. Nouvelot, Q. Ruiz, Requirements for a future refuelling protocol. Deliverable D2.6. Hg. v. Protocol for heavy-duty Hydrogen refuelling (PRHYDE), 2021. [Online]. Available: https://prhyde-cdn.s3-accelerate.amazonaws.com/wp-content/uploads/2021/07/15080917/PRHYDE_Deliverable-D2-6_Requirements-for-a-future-refuelling-protocol_final.pdf. (accessed: September 05, 2022)

[43] D. M. Dreistadt, J. Puszkiel, J.M. Bellosta von Colbe, G. Capurso, G. Steinebach, S. Meilinger, J. Jepsen, A Novel Emergency Gas-to-Power System Based on an Efficient and Long-Lasting Solid-State Hydride Storage System: Modeling and Experimental Validation, Energies 15 (2002) 844. https://doi.org/10.3390/en15030844

[44] E. Wienken, P. Krause, J. Warfsmann, J. Bellosta von Colbe, J. Jepsen, T. Klassen, J. Puszkiel, Book of abstract, Modeling and process simulation of a metal hydride tank coupled with a PEM electrolyzer, In *23rd World Hydrogen Energy Conference (WHEC 2022)*, Istanbul 26-30 June 2022, Dincer, I., Colphan, C. O., Ezan, M. A., Eds.. ISBN: 978-625-00-0843-0. Available: https://drive.google.com/file/d/10X1tZrIAAmJK7Aoj58QuyctCV_Qbw8LR/view [accessed: September 05, 2022].

[45] V. Mehta, Cooper, J.S. Review and analysis of PEM fuel cell design and manufacturing. J. Power Sources 2003, 114, 32–53.

[46] Power Cellution, https://powercellution.com/power-generation-system-5 (accessed: September 05, 2022)

[47] M. Cavo, E. Gadducci, M. Rivarolo, L. Magistri, A. Dellacasa, M. Romanello, G. Borgogna, C. Davico, Thermal integration of PEM Fuel Cells and metal hydrides storage system for Zero Emission Ultimate Ship (ZEUS), E3S Web of Conferences 334, 04004, 2022.

[48] Ø. Ulleberg, H. Ito, M. H. Maack, B. Ridell , S. Milese, N. Kelly, A. Iacobazzi, Modeling and Evaluation of Hydrogen Demonstration Systems, WHEC 16 / 13, 2006.

Integrated Design Methodology for Advanced Functional Materials

Denis Kramer*, Adrian Fortuin, Jiangming Cao, Aleena Anna Thomas
Helmut-Schmidt-University Hamburg / University of the Armed Forces
Hamburg, Germany
*d.kramer@hsu-hh.de

Claudio Pistidda*, Thi Thu Le, Thomas Klassen
Helmholtz-Zentrum Hereon, Institute for Hydrogen Technology
Geesthacht, Germany
*claudio.pistidda@hereon.de

Daniel Höche*, Min Deng
Helmholtz-Zentrum Hereon, Institute for Surface Science
Geesthacht, Germany
*daniel.hoeche@hereon.de

Michael Störmer*, Gnanavel Vaidhyanathan Krishnamurthy
Helmholtz-Zentrum Hereon, Institute for Photoelectrochemistry
Geesthacht, Germany
*michael.stoermer@hereon.de

***Abstract* – Engineering innovation and technological leadership increasingly depend on the timely availability of advanced functional materials. Development times of technology enabling materials, however, are still typically measured in decades. Within the Digital Materials Foundry, we develop and implement an integrated design methodology that equally draws on advanced high-throughput quantum mechanical simulations and automated combinatorial synthesis to dramatically accelerate the optimization of materials for a range of energy applications. Here we present our recent infrastructure advances as well as selected initial results from our research on hydrogen storage materials, meta-materials, magnesium batteries, and magneto-electrocatalysis.**

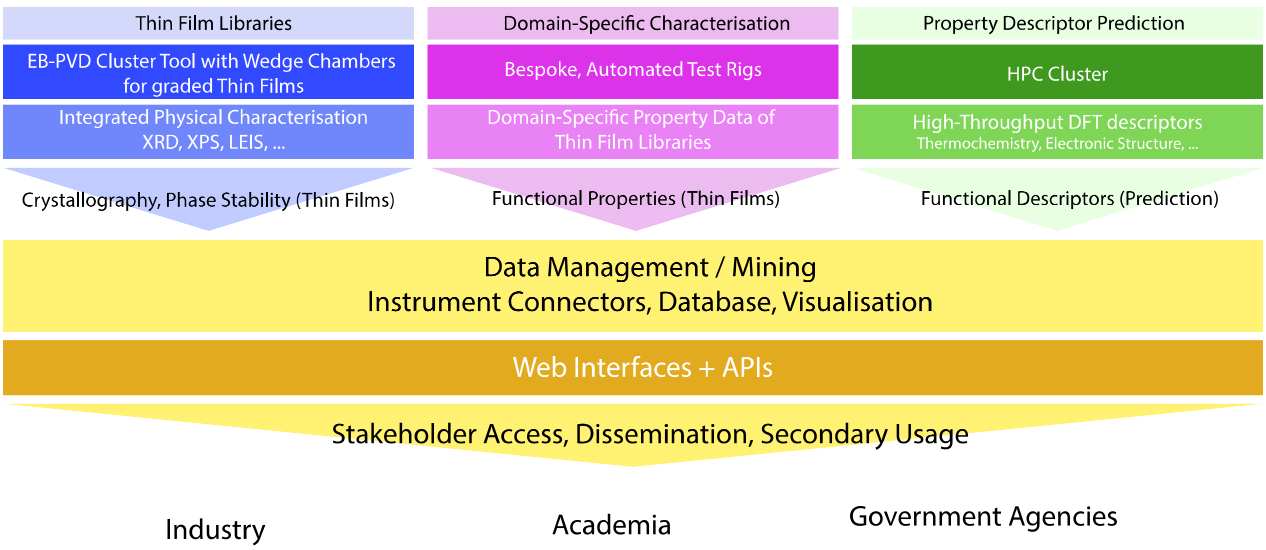
Materials Design, Density Functional Theory, Physical Vapour Deposition, Hydrogen Storage, Meta-Materials, Electrocatalysis.

I. Introduction

"Classical" Materials Science is not fit for the accelerated development cycles of the future. Traditionally, materials breakthroughs are often sparked by serendipitous discovery followed by many years of development and optimisation. For instance, the fundamental chemistry that enabled the recent advent of Li-Ion batteries was demonstrated by John Goodenough in 1980 [1], but it took eleven years for the first commercial application in consumer electronics by Sony in 1991 and almost 40 years for Li-Ion batteries to scale to high energy applications such as electric vehicles. Similarly, high surface area Pt oxygen reduction catalysts—now used in fuel cell cars—were already known in the 1960 [2], but it took almost 40 years to develop the fundamental understanding [3] to enable the rational development of Pt alloy catalysts around 2000 [4] that ultimately were utilised in Toyota's 2014 Mirai; a staggering 50+ years later!

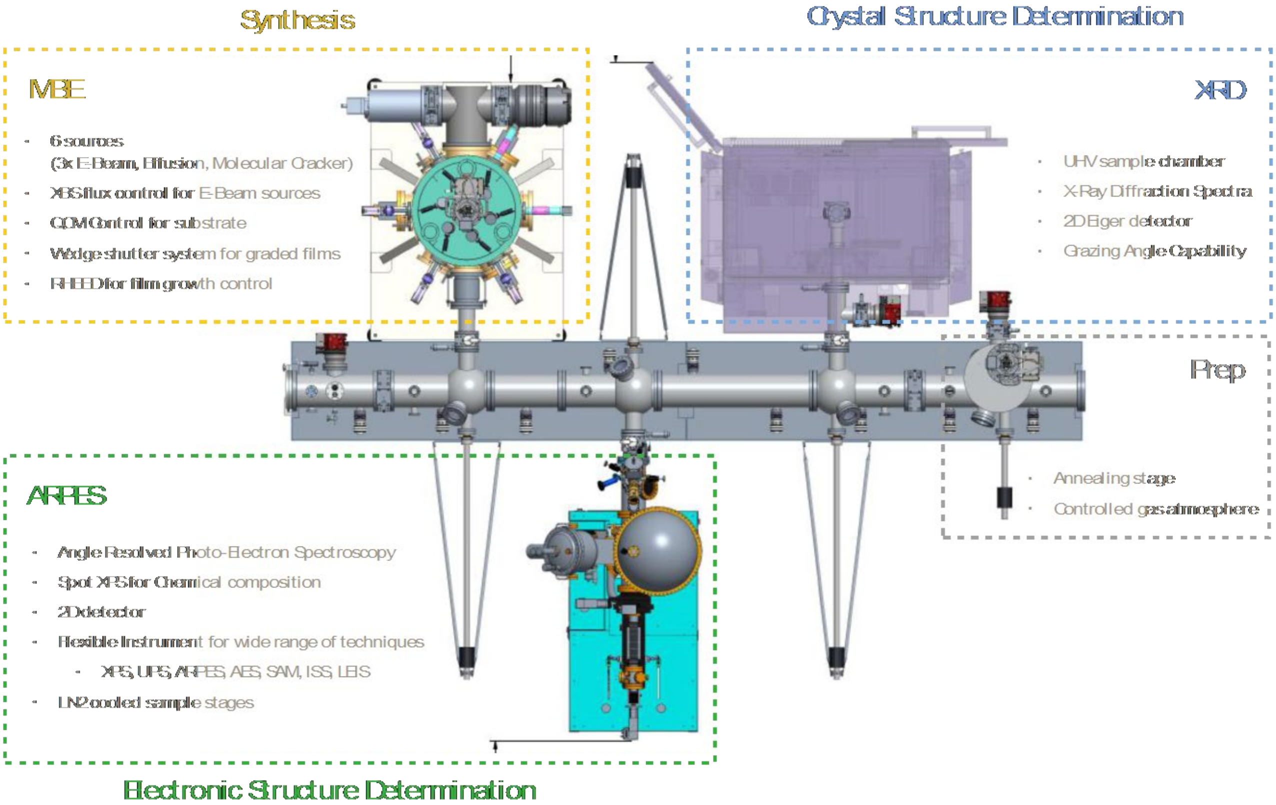
Two major paradigm shifts are underway in Materials Science that promise to significantly speed-up development and shorten times to commercialisation: (1) truly predictive *Computational Materials Design* (CMD) based on advanced and efficient quantum mechanical methods is now possible, and an impressive array of *functional descriptors* can be computed fully *in silico,* allowing for almost cost-free scaling of discovery/optimisation once a valid and computable descriptor is identified. (2) *Combinatorial Materials Science* (CMS) now allows it to synthesis materials libraries across chemical spaces with unprecedented speed followed by automated characterisation.

Whilst CMD and CMS are impressive methodological advancements, they both have shortcomings and difficulties



Figures 1: Pillars of the integrated materials design platform comprising advanced synthesis, characterization and modelling.

https://doi.org/10.24405/14528



FIGURES 2: PHYSICAL VAPOR DEPOSITION CLUSTER TOOL FOR THE DEPOSITION OF CHEMICALLY-GRADED THIN FILM LIBRARIES WITH INTEGRATED ANALYTICS FOR CRYSTAL STRUCTURE DETERMINATION AND ADVANCED X-RAY SPECTROSCOPY.

that need to be addressed to unlock their full potential. Interestingly, challenges are often complementary promising significant benefit from close coupling between CMD and CMS. This, however, has not yet happened in general, partially because the interdisciplinary nature and the needed disparate skillsets have led to distinct scientific communities that only now start to talk to each other.

II. METHODOLOGY

There is a clear opportunity for technological advance by exploiting the benefits of a fully integrated, digitised materials design methodology that equally draws on computational and combinatorial methodologies linked by a common data management and data mining platform. Such a platform has to comprise three pillars (cf. FIGURE 1): (1) combinatorial synthesis and characterisation of materials libraries, (2) modular, application-focused testing and screening of materials libraries, and (3) predictive modelling of materials properties in high-throughput mode, all feeding into sophisticated informatics for data management, visualisation and processing to bring things together.

A. Combinatorial synthesis

The ideal synthesis strategy has to be versatile, fast, reproducible and ideally yields materials systems that closely align with application environments. Especially, the demand for versatility and application relevance often leads to conflicts and necessary compromises.

Within the Digital Materials Foundry, we champion thin-film libraries synthesised by Physical Vapour Deposition (PVD) as model systems, because they allow for fast and reliable synthesis of an exceptionally broad spectrum of materials as well as standardised characterisation. The foundries unique combinatorial thin-film synthesis platform with integrated x-ray spectroscopy and diffraction is depicted in FIGURE 2. The platform is designed to synthesise metals, alloys, oxides and corrosive chemistries such as sulphides and other transition metal dichalcogenides as well as mixtures of these compounds. The platform comprises (1) a combinatorial physical vapor deposition chamber with six sources, (2) a preparation chamber for post-treatment of deposited films, (3) an x-ray spectrometer for elemental analysis and electronic structure determination, and (4) an x-ray diffractometer for crystal structure determination of deposited films.

The entire system is designed to operate in ultra-high vacuum (UHV) realising the demanding environment for molecular beam epitaxy (MBE). Although we do not generally aim for single crystal films, the cleanliness, purity and stoichiometric precision associated with MBE are of utmost importance. Films are deposited on two-inch wafer substrates with up to six sources with individual flux control allowing to vary stoichiometry during deposition; and adjustable substate shutters allow to mask varying areas during deposition to create chemically graded films. Hence, a single wafer can carry a library of tens if not hundreds of stoichiometries. The setup comprises three e-beam evaporators to deposit metals, a molecular cracker to provide atomic H, O, and N, and specialised sources for S, C, and P. Due to this variety of sources, almost the entire periodic table from H to Au is available (excluding noble gases). Finally, the system is easily extendable with additional sources such as magnetrons or effusion cells to fulfil future needs.

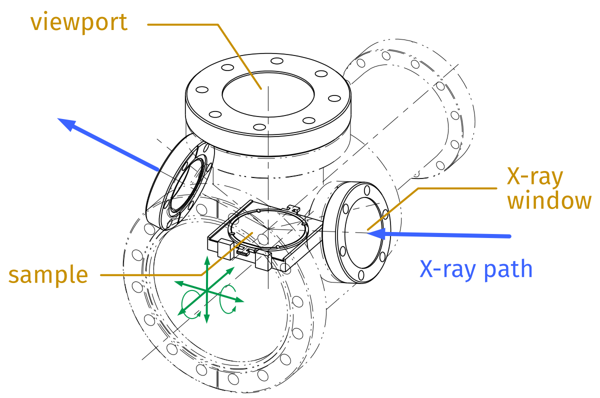
Deposited films can be annealed in a separate preparation chamber under controlled atmosphere to ensure well crystalised films with the controlled gas atmosphere providing additional means to control chemical composition as well as film morphology [5].

B. *Physical Characterisation*

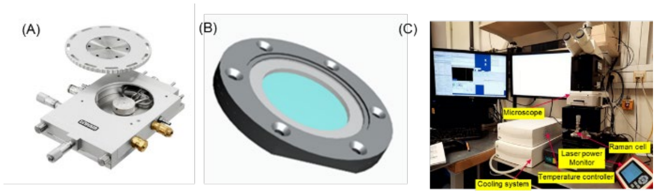
Understanding the physical properties of deposited films is crucial to map out structure-property relationships. The platform, therefore, integrates two sophisticated analytical tools within the UHV environment: (1) an X-ray spectrometer for determining stoichiometry and electronic structure and (2) an X-ray diffractometer to determine crystal structure. To the best of our knowledge, the integration of both within one UHV environment is a unique feature enabling comprehensive characterisation of even highly reactive materials, because it eliminates any chance of contamination or degradation during transfers.

The x-ray spectrometer, developed and manufactured by Specs, ensures the ability to confirm stoichiometry of synthesised films via X-ray photoelectron spectroscopy (XPS). Elemental composition is determined by analysing the energy spectrum of released photoelectrons with each element providing a characteristic spectrum [6]. Substrates are mounted on an UHV manipulator, which enables lateral translations to scan across the entire area of the two-inch wafers for spot characterisation of composition across chemically graded films. The X-ray spectrometer also comprises a low-energy X-ray source and angle-resolved detector to study the electronic structure of valence electrons close to the Fermi level. Angle-resolved photo-electron spectroscopy (ARPES) provides highly valuable experimental access to the electronic structure of compounds that defines their chemical (and optical) reactivity and provides a direct experimental twin to band structure calculations—promising direct experimental validation of predictions even for electronically challenging compounds such as strongly correlated oxides.

Finally, the platform incorporates a x-ray diffractometer (XRD) within the UHV environment. A highly customised Bruker D8 Discover diffractometer is developed to house an UHV measurement chamber with manipulator and pass a UHV transfer arm through the back of the diffractometer. This novel prototype design developed with Bruker enables the measurement of X-ray diffractograms without samples ever leaving the UHV environment. The sample chamber design



FIGURES 3: UHV SAMPLE CHAMBER FOR X-RAY DIFFRACTION STUDIES WITH X-RAY WINDOW AND MOVABLE SAMPLE STAGE.



FIGURES 4: RAMAN MEASUREMENT SETUP FOR AIR-TIGHT THIN-FILM SAMPLES: (A, B) RAMAN CELL, (C) SET UP OF RAMAN MEASUREMENT

(cf. FIGURE 3) incorporates two x-ray windows to pass the X-ray beam from the source to the sample and scattered X-rays back to the detector, which both are housed outside the UHV environment. The sample stage is mounted onto a manipulator that allows to translate and rotate the sample to align the thin films and scan the x-ray spot across the entire two-inch wafers, enabling local determination of the crystal structure. The need for five axis manipulation (three translations, two rotations) implies challenges for the manipulator design compounded by the limited space to host the manipulator within the XRD enclosure. This has been overcome by a combination of expanding the XRD enclosure and developing a highly compact manipulator design.

C. *Domain-specific characterisation*

Thin films provide model systems to gauge materials properties in well-controlled and—to some degree—simplified experimental setups. They allow to estimate relevant properties of materials for a given application, but rarely provide quantitative measures that exactly match performance under application conditions. They are a highly useful intermediary systems to quickly identify “hotspots” in phase space but require bespoke measurement setups. Because these setups are necessarily application-specific, a modular strategy is attractive, where an array of independent experimental platforms is available utilising standardised thin film substates.

Raman holders (cf. FIGURE 4A,B) are used to measure *in-situ* thin hydride films under different H_2 pressures (10^{-2} bar – 15 bar) and temperatures (-60 °C – 500 °C). By using an *in-house* built *ex-situ* Raman cell (cf. FIGURE 4B), samples with dimensions up to 2×2 inches produced by PVD can be investigated. All Raman measurements (*in-situ* and *ex-situ*) are carried out using a WITec confocal Raman microscope (Alpha300 R) equipped with 523 nm and 633 nm lasers (cf. FIGURE 4C).

A multi-electrode electrochemical cell is designed for high throughput screening of alloy-type anode materials for Mg-ion batteries (MIB). The cell enables simultaneous electrochemical measurements, like cyclic voltammetry (CV), of micro-anodes in the thin film array (e.g. 4×4) manufactured by PVD. A three-electrode system is utilised for the electrochemical study in conventional non-corrosive Mg battery electrolytes (e.g. 0.5 M $Mg(ClO_4)_2$ in acetonitrile (I)). An Ag wire is used as the quasi-reference electrode (QRE). The stability of the potential of the Ag wire with time in Mg battery electrolytes can be examined with an internal reference such as the ferrocene/ferrocenium (Fc/Fc^+) couple, which shows negligible redox change in organic solutions [7].

D. *High-Throughput Materials Modelling*

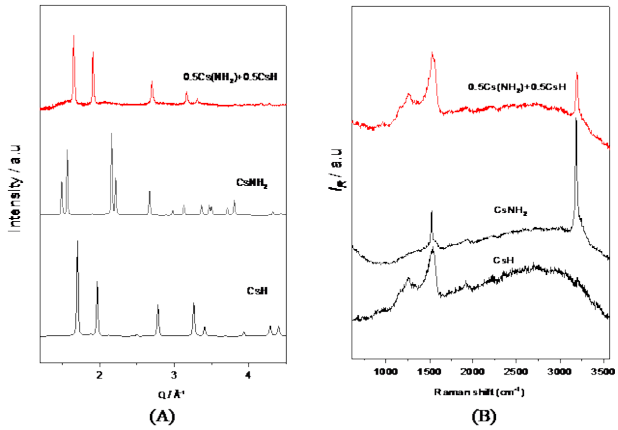
Ab initio modeling, based on Density-Functional-Theory (DFT), has matured into a highly predictive theory to gauge a very wide range of materials properties. Fundamental properties such as phase stability, electronic structure and thermo-chemistry have become routine calculations that can be fully automated [8]. In addition, properties such as ion mobility or surface reactivity that require more advanced calculations are increasingly encapsulated within automated workflows promising similar levels of automation and scaling in the near future.

We actively develop our digital infrastructure, which consists of a selection of third-party codes combined by in-house "glue codes" that manage computations and data storage and processing, complemented by a visualisation layer. We strongly rely on a small set of mature DFT codes to predict materials properties [9]. DFT calculations are managed with the "atomate" framework [10] allowing for automated computation of pre-defined workflows and sophisticated error handling. Through in-house codes, this HT-DFT layer is coupled with advanced search strategies to explore phase space. Commonly, this takes the form of heuristics or statistic models that we construct from a limited set of DFT calculations spanning the chemical space of interest [11]. For even more advanced searches, we construct model Hamiltonians that capture the physics of that particular chemical space, but compute orders of magnitude faster than DFT to drive Monte Carlo or even brute force explorations of phase space. For instance, we often utilise cluster expansions and the CASM code [12] to efficiently map the energy landscape of substitutional disorder in a given host structure.

III. Applications

A. Hydrogen storage

Amide-hydride-based materials, such as $LiNH_2$-LiH [13], and $Mg(NH_2)_2$-2LiH [14] are considered potential hydrogen storage candidates for mobile and stationary applications owing to their high hydrogen storage capacity and favourable thermodynamics, which in many cases allow the reversible release of hydrogen at temperatures below 150 °C. However, one of the main problems of amide-hydride systems is the sluggish dehydrogenation/re-hydrogenation kinetics, which limits their practical applications. It has been found that the formation of reaction intermediates such as hydride-amide solid solutions might influence the material properties. Among the recently discovered amide-hydride solid solutions are $Li_{2-x}NH_{1+x}$, $K(NH_2)_xH_{1-x}$, $Rb(NH_2)_xH_{1-x}$ in $LiNH_2$-LiH, KNH_2-KH, and $RbNH_2$-RbH systems, respectively. These solid solutions are formed by the exchange of amide/hydride anions at the amide/hydride interface. The substitution of anion species taking place at the interfaces is suggested to facilitate ionic transport in these systems. Similar to the systems KNH_2-KH [15] and $RbNH_2$-RbH [16], a mixed cation amid-hydride solid solution is likely to be formed in the system $CsNH_2$-CsH. To verify this hypothesis, initial tests were performed. According to XRD data (cf. Figure 5A), the diffraction reflection of a single cubic phase, which has a similar structural geometry as the CsH, is visible for the 1:1 composition. Besides, Raman spectra (cf. Figure 5B), exhibit a shift to higher frequencies of the N-H bond, signifying a substitution of H^- and $[NH_2]^-$ in the 1:1 composition. As shown in Figure 6, the unit cell of the solid solution expands with the increase in amide amount, indicating the $[NH_2]^-/H^-$ substitution taking place between amide and hydride. Lattice parameters obtained experimentally by Rietveld refinement agree well with Vegard´s law, suggesting an ideal behaviour for the solid solution ($\Delta H_{mix} \sim 0$, and $\Delta V_{mix} \sim 0$). In the next step, the formation of the solid solution will be assessed by proton double quantum experiments (^{1}H 2D SS MAS NMR)



Figures 5: (A) XRD patterns and (B) Raman spectra of the starting and mixed hydrogen storage materials.

and subsequently evaluated by theoretical studies via *First Principles* calculations (e.g. nuclear spin-spin coupling). The combination of experimental evidence and theoretical predictions could provide an appropriate way for predicting and assessing the structural properties of the material.

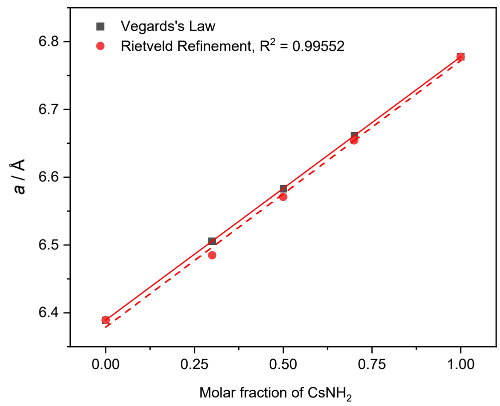
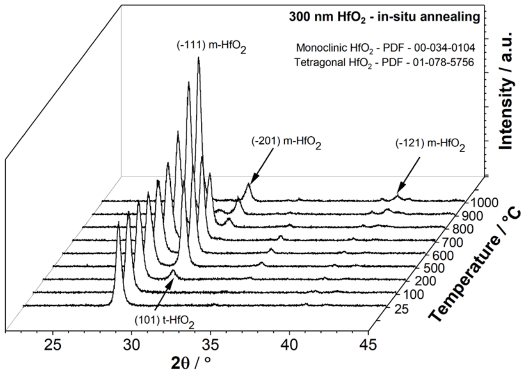


Figure 6: Unit cell parameters of the $Cs(NH_2)_xH_{1-x}$ solid solution as a function of the amide fraction obtained from Rietveld refinement of the XRD data and Vegard's law.

B. Metamaterials

A selective emitter can enhance the efficiency of a thermophotovoltaic (TPV) system by suppressing radiation above the cut-off wavelength of a low bandgap photovoltaic (PV) cell [17]. Unfortunately, there exists no material in nature that shows selective emission. A thin-film metamaterial containing alternate layers of a metal and a dielectric in the nanometre scale, however, can be artificially fabricated to engineer selective emitters [18]. The selective emitter functions like a blackbody, and it needs to operate at temperatures above 1000 °C for a long-time posing challenges for durability. Therefore, refractory materials like W and HfO_2 are best suited for thermophotovoltaic applications.

At high working temperatures above 1000 °C, thermally activated degradation processes like diffusion, oxidation and phase transformation come into play. Figure 7 shows in-situ annealed diffractograms of a single 300 nm thick HfO_2 layer from room temperature up to 1000 °C. The as-prepared HfO_2 film contains two phases, a monoclinic and an amorphous phase. On heating the layer to 200 °C, the amorphous phase first transforms into the tetragonal phase, and upon further heating above 800 °C, the tetragonal phase transforms into the stable monoclinic phase [19]. At 1000 °C, the entire film exists only in the monoclinic phase with no reverse phase transformation observed on cooling down. A phase change from tetragonal to monoclinic structure increases the unit cell volume by 3.7%. In order to accommodate the volume change, voids are generated in the HfO_2 layer.

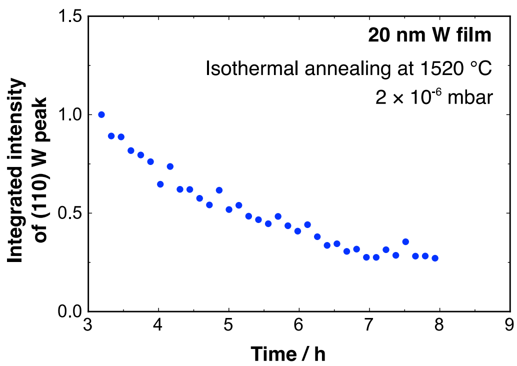


FIGURES 7: DIFFRACTOGRAMS OF AN IN-SITU ANNEALED 300 NM SINGLE HfO_2 LAYER FROM 25 °C UP TO 1000 °C AT 3×10^{-6} MBAR. AT 200 °C, A NEW (101) TETRAGONAL HfO_2 PHASE EMERGES AT 30.3°. ON FURTHER REACHING 800 °C, THE (101) TETRAGONAL PEAK VANISHES AND ONLY PEAKS FROM MONOCLINIC HfO_2 (-111), (-201) AND (-121) ARE VISIBLE AT 1000 °C.

A 20 nm single tungsten layer has a bcc crystal structure, and the thermal stability was validated by an in-situ isothermal annealing experiment at 1520 °C for 6 h at 3×10^{-6} mbar. The integrated intensity of the XRD diffraction pattern correlates with the volume fraction of a phase in the material. Here, the normalised integrated intensity of the (110) bcc tungsten peak as a function of time as shown in FIGURE 8 is used. A gradual drop in intensity is observed due to the loss of scatterers from the film, as tungsten gets oxidised by residual oxygen present in the atmosphere of the annealing chamber [19]. The formed tungsten oxide sublimates rapidly at such high temperatures. Future work is aimed toward utilizing the PVD cluster tool to prepare dielectric layers with a stable phase and dope the metallic layers to improve the oxidation resistance and durability in the multilayer stack.

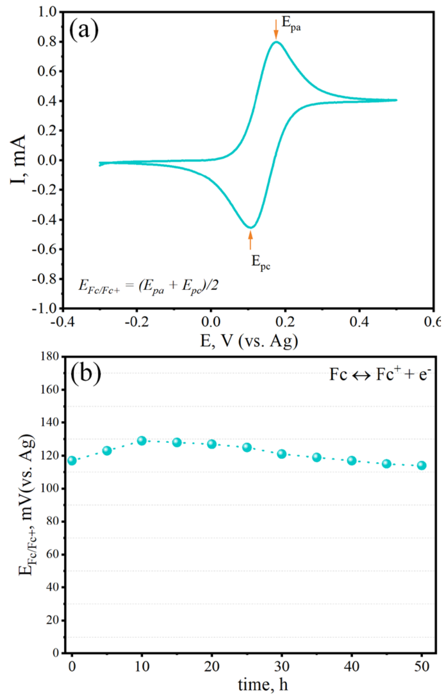
C. *Magnesium batteries*

The adoption of alloy-type anodes (like Mg3Bi2 [20]) for magnesium ion batteries (MIB) could bypass the passivation issue in conventional non-corrosive electrolytes, which have



FIGURES 8: THE INTEGRATED INTENSITY OF (110) W PEAK IN A 20 NM SINGLE LAYER AS A FUNCTION OF TIME DURING ISOTHERMAL ANNEALING AT 1520 °C AND 3×10^{-6} MBAR. A GRADUAL DROP IN INTENSITY IS OBSERVED AS A RESULT OF LOSS IN THE FILM, DUE TO OXIDATION TUNGSTEN AND LAYER SUBLIMATION OF VOLATILE TUNGSTEN OXIDES.

good compatibility with some high voltage/high capacity cathode materials. The combination of alloy-type anodes, non-corrosive conventional electrolytes and suitable cathode materials could be a new way for next-generation high-performance MIB, providing high capacity alloy anodes that can work properly in conventional electrolytes. This platform enables the fast and reliable synthesis of diverse alloy-type



FIGURES 9: (A) CV CURVES OBTAINED IN 0.5 M $Mg(ClO4)2$/ACN SOLUTION CONTAINING 0.05 M FC WITH PT WORKING ELECTRODE, ACTIVATED CARBON CLOTH COUNTER ELECTRODE AND AG WIRE REFERENCE ELECTRODE; (B) STABILITY OF $E_{Fc/Fc+}$ VS. AG WITH TIME.

anode thin films via PVD and functional screening based on high throughput electrochemical measurements. However, before the implementation of this methodology, a reference electrode that can work reliably in conventional MIB electrolytes is required to ensure accurate electrochemical testing. Widely adopted Mg foils cannot be utilised in this scenario due to the passivation of pure Mg metal in conventional electrolytes. Ag wire, as a common alternative quasi-reference electrode (QRE), could be a good candidate, but the stability of its potential in the electrolytes of interest has to be demonstrated.

The Fc/Fc^+ redox couple has a consistent redox potential in diverse organic solutions [21]. Therefore, it can be used as an internal standard reference for examining the stability of Ag wires when serving as a QRE. The redox potential of Fc/Fc^+ versus Ag QRE ($E_{Fc/Fc+}$ vs. Ag) can be determined from the CV curve obtained in 0.5 M $Mg(ClO_4)_2$/I solution containing 0.05 M Fc with a Pt working electrode, activated carbon cloth counter electrode and Ag reference electrode (cf. FIGURE 9A). On this basis, the stability of $E_{Fc/Fc+}$ vs. Ag with time represents the stability of the Ag QRE in the electrolyte. FIGURE 9B shows the variation of $E_{Fc/Fc+}$ vs. Ag with time, indicating a potential shift of around 20 mV within 50h, which is sufficiently small for the short-time electrochemical measurements employed during the fast screening of anode materials.

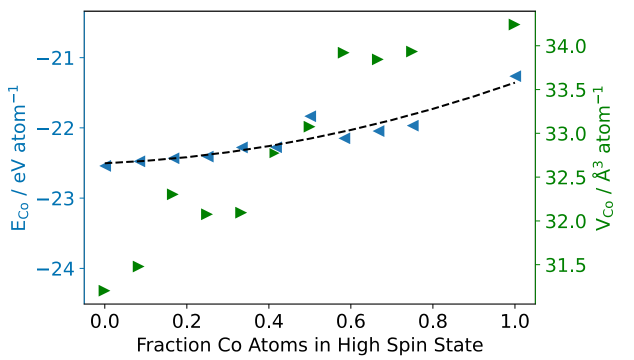
The hardness of an Ag wire (e.g. with 0.5 mm diameter) allows it to be a freestanding reference electrode. The combination of a Pt wire counter electrode and an Ag wire reference electrode enables easy assembly of the multi-electrode electrochemical testing cell. In the next stage, the compositionally graded thin film array manufactured by PVD will be characterised via the electrochemical testing rig consisting of the multi-electrode cell and a multi-channel potentiostat. Composition-dependant Mg plating/striping reversibility and cycling stability of the anode materials will be evaluated. Data will be adopted for data mining and the construction of digital design maps based on Density-Functional-Theory (DFT) and other modelling tools.

D. Magneto-Electrocatalysis

Utilising interactions with magnetic fields is an increasingly popular approach in materials science. This provides a novel opportunity to change the energy landscape during material synthesis. In heterogeneous catalysis, this promises materials that catalyse alternative mechanistic pathways for reactions of interest, e.g., the oxygen evolution reaction (OER) in water electrolysis.

One approach is to apply a strong magnetic field *in-situ* using ferro- and para-magnetic materials during OER [22]. Due to the bulk electron spin alignment, the additional magnetic field may provide a pathway to crystallising materials that can exist in different electronic states. For example, Co^{3+} has six electrons occupying its *d*-orbitals. In an octahedral configuration, these electrons can occupy a low spin (LS) state where they fill all three t_{2g} orbitals. Alternatively, a high spin (HS) state can be synthesized, where one electron occupies each of the three t_{2g} orbitals and the two e_g orbitals, with the remaining electron spin-pairing the electron in the lowest energy orbital [23]. In the example of Co^{3+}, the LS configuration has a $\mu_s = 0$ and the HS configuration has a $\mu_s = 4$, where μ_s is the magnetic moment in units of Bohr's magneton. Hence, only the HS state can energetically couple with an external magnetic field. The significance of different crystal spin states are: (i) HS states usually lead to larger lattice constants and (ii) it interacts with adsorbates differently due to differences in orbital bonding.

We carried out *First Principles* calculations of the total energy for the CoO(OH) system, using the generalized-gradient-approximation to Density Functional Theory (DFT) as parameterized by Perdew and Wang [24]. The Kohn-Sham orbitals are expanded in a plane-wave basis with a cutoff of E_{cutoff} = 520 eV. The electronic density was computed self-consistently until the variation was below the threshold of 10^{-6} eV. Spin-polarised calculations are performed on a 2×2×1 supercell with μ_s explicitly initialised as $\mu_s = 0$ for LS Co^{3+}. The position of the ions in the unit cell were relaxed until the residual forces were below the threshold of 10^{-2} eV Å^{-1}. A Hubbard U correction was applied to Co as described by the Materials Project [8] with U = 3.32 eV. Calculations were repeated by initialising $\mu_s = 4$ for an increasing number of Co atoms at random, until the HS state was reached.



FIGURES 10: CALCULATED ENERGY (LEFT AXIS) AND LATTICE VOLUME (RIGHT AXIS) PER COBALT ATOM AS A FUNCTION OF FRACTION OF TOTAL COBALT ATOMS IN A HIGH SPIN STATE. THE GREY AREA INDICATES THE 95% CONFIDENCE INTERVAL FOR THE QUADRATIC FIT TO THE CALCULATED ENERGY.

The preliminary results are presented in FIGURE 10. As expected, the HS state occupies a larger lattice volume. The energy difference is on the order of 1 eV per Co atom between LS and HS states. A quadratic equation can be fitted to the calculated energy, indicating that next-neighbour interactions are relevant and need to be captured by a model Hamilton. Monte Carlo methods can then be used to quantify lateral interactions between spin states through pair correlation functions. Because it is unlikely that realistic magnetic fields can overcome an energy penalty of 1 eV by themselves, our interest currently shifts to the exchange-coupled decay length of a HS state and whether it is comparable with nanometre thick surface layers to provide an alternative explanation for experimental observations.

IV. CONCLUSION AND OUTLOOK

We are well advanced with our aim to implement a powerful and unique integrated platform to accelerate materials design for energy applications. Each of the three pillars is progressing: (1) the PVD cluster tool design is completed and currently in manufacturing, (2) the first set of domain-specific test rigs produces initial results, and (3) we have successfully transitioned our computational infrastructure to the new HSUper platform [25] with work ongoing to integrate a large-scale data repository.

In the next phase, we look forward to commission the PVD cluster tool, finalise and optimise the test rigs, and integrate all work strands with our data management to then focus on developing technology-enabling materials for renewable energy applications.

ACKNOLODGEMENT

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project Integrated Design Methodology for Advanced Functional Materials].

REFERENCES

[1] J.B. Goodenough, Y. Kim, *Chem. Mater*. **22** (2010) 587.
[2] W.T. Grubb, D.W. McKee, *Nature* **210** (1966) 192.
[3] B. Hammer, J. Norskov, *Nature* **376** (1995) 238.
[4] N.M. Markovic *et al.*, *Fuel Cells* **1**(2) (2001) 105.
[5] A. Rabis *et al.*, *J. Phys. Chem. C* **118** (2014) 11292.
[6] G. Greczynski, L. Hultman, *Prog. Mater. Sci.* **107** (2020) 100591.
[7] L. Fabbrizzi, *ChemTexts* **6** (2022) 22.
[8] A. Jain *et al.*, *APL Materials* **1** (2013) 011002.
[9] G. Kresse, J. Hafner, *Phys. Rev. B* **47** (1993) 558; R. Dovesi *et al.*, *WIREs Comput. Mol. Sci.* **8** (2018) e1360; J.C.A. Pentice et al., *J. Chem. Phys.* **152** (2020) 174111.
[10] K. Mathew *et al.*, *Comput. Mater. Sci.* **139** (2017) 140.
[11] A. Silva *et al.*, *NPJ Comput. Mater.* **8** (2022) 178.
[12] A. Van der Ven, *An. Rev. Mater. Res.* **48** (2018) 27.
[13] P. Chen *et al.*, *Nature* **420** (2002) 302.

[14] H. Cao *et al.*, *Prog. Nat. Sci.: Mater. Int.* **22** (2012) 550.
[15] A. Santoru *et al.*, *Phys. Chem. Chem. Phys*. **18** (2016) 3910.
[16] A. Santoru *et al.*, *Inorg. Chem.* **57** (2018) 3197.
[17] R. Sakakibara et al., *Sol. Energy Mater. Sol. Cells* **238 (**2022) 111536.
[18] Z. Wang *et al.*, *Sol Energy Mater. Sol. Cells* **238** (2022) 111554.
[19] G. Krishnamurthy *et al.*, *Sci. Rep.* **11** (2021) 3330.
[20] Y.H. Tan et al., *ACS Nano* **12** (2018) 5856.
[21] G. Gritzner, J. Kůta, *Electrochim. Acta* **29** (1984) 869.
[22] F.A. Garcés-Pineda *et al., Nat. Energy* **4** (2019) 519; X. Ren *et al.*, *Nat. Commun.* **12** (2021) 2608; T. Wu *et al.*, *Nat. Commun.* **12** (2021) 6251.
[23] T. Kambara, *J. Chem. Phys.* **70** (1979) 4199; R. Zimmermann, E. König, *J. Phys. Chem. Solids.* **38** (1977) 779.
[24] J. P. Perdew. Y. Wang, *Phys. Rev. B* **45** (1992) 13244.
[25] https://www.hsu-hh.de/hpc/en/hsuper-2/.

Power-Hardware-in-the-Loop Testumgebung zur Integration von digitalen Zwillingen verschiedener elektrischer Mobilitätsträger

Andreas Stadler*, Nils Pinke, Detlef Schulz
Professur für Elektrische Energiesysteme
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Hamburg, Deutschland
*andreas.stadler@hsu-hh.de

***Kurzfassung* – Im Projekt „Durchgehend digital gesteuerte Netz- und Ladeinfrastruktur für Land-, Luft- und Wasserelektromobilität“ (dtec emob) wird mithilfe von Forschungslaboren ein KI-basiertes Energiemanagementsystem entwickelt. Dabei liegen Forschungsschwerpunkte auf der Analyse von Ladeinfrastruktur und Elektromobilitätsträgern und den Auswirkungen aufeinander sowie auf das elektrische Netz. Im Rahmen einer flexiblen und erweiterbaren Power-Hardware-in-the-Loop-Testumgebung sollen die verschiedenen Forschungsfelder miteinander verbunden und erprobt werden. Diese umfassen einen Echtzeitsimulator, digitale Zwillinge, Netzsteuerungen und einen Netzsimulator zur Einbindung von realer Ladeinfrastruktur. Dieser Bericht beschreibt die Grundlagen der einzelnen Bestandteile und zeigt eine Umsetzung zur Validierung des Gesamtkonzeptes. Zudem wird der weitere Entwicklungsplan der Testumgebung im Projekt dtec emob dargestellt und mögliche Forschungsfragen, die beantwortet werden sollen, aufgezeigt.**

Stichworte – PHIL, Elektromobilität, Ladeinfrastruktur, Microgrid, Digitaler Zwilling, dtec.bw

NOMENKLATUR

dtec emob	Durchgehend digital gesteuerte Netz- und Ladeinfrastruktur für Land-, Luft- und Wasserelektromobilität
DUT	Device under test
DZ	Digitaler Zwilling
EMT	Elektromobilitätsträger
HIL	Hardware-in-the-Loop
KI	Künstliche Intelligenz
LIS	Ladeinfrastruktur
MC	Mikrocontroller
PHIL	Power-Hardware-in-the-Loop
SOH	State of health
SMPA	Switched-Mode-Power-Amplifier
TRL	Technology Readiness Level
V2G	Vehicle-to-grid
V2H	Vehicle-to-home
a, b	Parameter der simulierten Ladekurve
P in W	Leistung
SOC, SOC_{UP} in %	State of charge, State of charge des Ladeumschaltpunkts
t, t_0 in s	Zeit, Startzeit
t_c, t_i, t_s, t_w in s	Dauer der: Berechnungen, Verarbeitung der Eingänge, Zeitschritte, Wartezeit

I. EINLEITUNG

Im Projekt „Durchgehend digital gesteuerte Netz- und Ladeinfrastruktur für Land-, Luft- und Wasserelektromobilität“ (dtec emob) wird ein auf künstlicher Intelligenz (KI) basierendes Energiemanagement für das Verteilnetz entwickelt. Grundlegend dafür sind Forschungslabore, in denen intelligente Lade- und Lastmanagementsysteme zur optimierten Einbringung von Elektromobilität in die bestehenden und zur Reduzierung des Ausbaus der kommenden Netzbestandteile entwickelt, aufgebaut, getestet und validiert werden.

Eine zentrales Forschungslabor stellt die aufgebaute „Power-Hardware-in-the-Loop“ (PHIL)-Testumgebung an der Professur für Elektrische Energiesysteme der Helmut-Schmidt-Universität dar. In dieser Testumgebung werden verschiedenen Projektbestandteile und Forschungsschwerpunkte von dtec emob verknüpft.

„Hardware-in-the-Loop“ (HIL)-Systeme bieten eine Möglichkeit hardwareseitig implementierte Regler unter sicheren und reproduzierbaren Bedingungen zu testen. Der grundlegende Aufbau wird in ABBILDUNG 1 dargestellt. Auf der Simulatorseite wird das Zielsystem simuliert und die sich daraus ableitenden Signale für den Regler „device under test“ (DUT) erstellt. Die Signale liegen, wie im realen System, an den Hardwareeingänge des Reglers an. Die daraus resultierenden Ausgangs- und Steuersignale des Reglers werden gegebenenfalls über Sensoren zurück an die

https://doi.org/10.24405/14529

Systemsimulation geleitet und somit das Gesamtsystem aktualisiert. Auf diese Weise werden sowohl der Regler als auch sein Verhalten kontinuierlich geprüft und validiert.

Der beschriebene Aufbau ermöglicht insbesondere auch Tests in frühen Entwicklungsstadien und unter Extrembedingungen, welche in realen Systemen nicht oder nur schwer abbildbar sind.

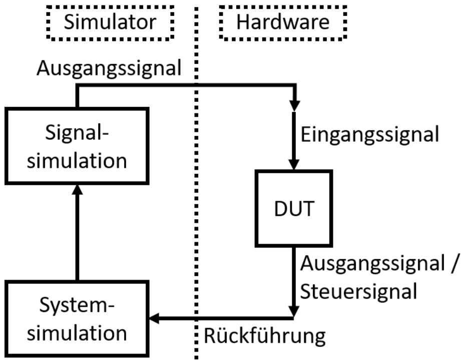


ABBILDUNG 1: GRUNDLEGENDER AUFBAU HIL.

Eine Erweiterung des Systems stellen PHIL-Testsysteme dar. Dabei wird das System auf der Hardwareseite um eine Leistungskomponente ergänzt. Dieses wird üblicherweise mit Hilfe eines Leistungsverstärkers realisiert, welcher analog zum DUT ein Steuersignal von der Simulationsseite erhält und die Bereitstellung von Strom und Spannung parametrisiert. Je nach Aufbau und Funktion können somit Teile oder das gesamte DUT unter realen Bedingungen getestet werden. Insbesondere kann, zusätzlich zu den an den Ausgängen entnehmbaren Signalen, in HIL-Tests auch das elektrische Verhalten untersucht werden.

HIL- und PHIL-Tests sind in Forschung und Entwicklung weit verbreitet und werden für diverse Zielsysteme und mit verschiedenen Zielen eingesetzt. Im Projekt dtec emob wird ein besonderer Fokus auf die Integration von Elektromobilität in Teil- oder Gesamtbereiche eines definierten Niederspannungsnetzes gelegt. Es werden mehrere Forschungsthemen und -ziele bearbeitet:

- Die einzelnen entstehenden Versuchsaufbauten im Bereich der Elektromobilität werden unter Realbedingungen überprüft. Zudem sind umfassende Tests unter realen Bedingungen durchführbar.
- Die Netzrückwirkungen von realer Ladeinfrastruktur (LIS) verschiedener Elektromobilitätsträger (EMT) kann unter Laborbedingungen untersucht werden.
- Die Kommunikation zwischen LIS, EMT, Messsystem und Netzsteuerung kann kalibriert und validiert werden.
- Die verschiedenen Forschungsbereiche des Projektes wie zum Beispiel Netzsteuerung, digitale Zwillinge (DZ) und Verkehrsflüsse werden miteinander zu einem Gesamtsystem verknüpft und dessen Funktionsfähigkeit validiert.
- Die Rückwirkungen und Einflüsse aufeinander von konventioneller unidirektionaler LIS und bidirektionaler LIS für die Rückspeisung ins Stromnetz („vehicle to grid“, V2G) und Heimnetz („vehicle to home“, V2H) wird analysiert.
- Die Steuerbarkeit von realer LIS (konventionell und V2G / V2H) wird überprüft.

Die aktuellen Konzepte und Umsetzungen des geplanten PHIL-Systems im Projekt dtec emob werden im folgenden Bericht aufgezeigt. In Kapitel II werden das Konzept und der Aufbau sowie die einzelnen Bestandteile beschrieben. Kapitel III zeigt aktuelle Funktionstests und gibt den Technologiereifegrad („Technology Readiness Level“, TRL) der im Projekt entwickelten Komponenten wieder. In Kapitel IV wird das weitere Vorgehen beschrieben.

II. AUFBAU

Das Konzept der in dtec emob umgesetzten PHIL-Testumgebung und die zentralen Bestandteile für konventionelle AC-basierte Ladeinfrastruktur wird in ABBILDUNG 2 dargestellt.

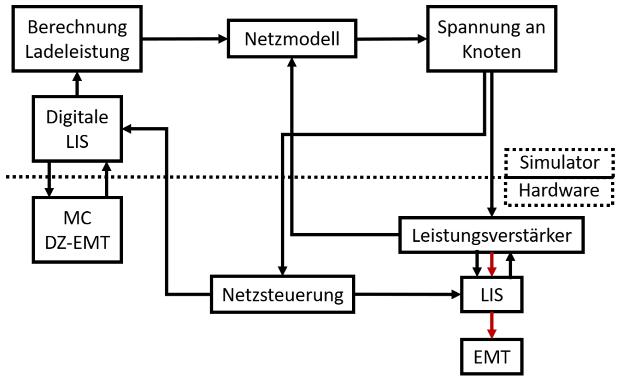


ABBILDUNG 2: PHIL KONZEPT FÜR AC-LIS IM PROJEKT DTEC EMOB – PFEILE SCHWARZ: KOMMUNIKATION, ROT: ENERGIEFLUSS.

Wie einführend beschrieben, lässt sich der Aufbau in diesem Bericht in einen Simulatorteil und einen Hardwareteil unterteilen. Der Simulatorteil wird mittels eines Echtzeitsimulators (Absatz II.A) umgesetzt. Die Hardwareseite beinhaltet digitale Zwillinge (Absatz II.C), die Netzsteuerung (Absatz II.D) und die „Power-Hardware“ (Absatz II.B), bestehend aus dem Leistungsverstärker, der Ladeinfrastruktur und dem Elektromobilitätsträger.

Zentraler Aspekt des Simulatorteils ist das untersuchte Niederspannungsnetz, hier werden sowohl Netzkomponenten als auch die elektrischen Lasten an den einzelnen Netzanschlusspunkten abgebildet. Die Eingangsparameter zur Berechnung der Netzzustände resultieren aus den Einflüssen der fluktuierenden Lasten und Erzeugerleistungen an den einzelnen Anschlusspunkten. Die Ausgangsparameter sind Netzinformationen wie z.B. die Spannungen an den Knoten und die prozentuale Transformatorauslastung. Über die Ein- und Ausgänge findet die Verknüpfung zwischen der Hardware- und Simulatorseite statt:

- Die Spannung am Power-Hardware-Knoten wird an den Leistungsverstärker übergeben, welcher das simulierte Spannungsverhalten am Knoten abbilden kann.
- Die Ladeleistungen der DZ und realen EMT werden an das Netzmodell übermittelt, auf diese Weise wird eine Berechnung der aktuellen Netzzustände ermöglicht.
- Teile der berechneten Parameter werden an die Netzsteuerung weitergegeben. Dadurch kann die optimale Regelstrategie bestimmt werden.

Im Folgenden werden die einzelnen Bestandteile, sowie die stattfindende Kommunikation, die Funktionen und die Umsetzung beschrieben.

A. Echtzeitsimulator

Werden Hardwaresysteme in (P)HIL-Tests untersucht, müssen die physischen Signale, welche von der Simulationsseite an das DUT geschickt werden, der Realität im späteren Anwendungsfall entsprechen. Dies gilt insbesondere für das dynamische Systemverhalten.

Dabei müssen die für jeden Zeitschritt t_s durchgeführten Systemberechnungen nicht nur ausreichend schnell, sondern auch in definierten, gleichmäßigen Abständen erfolgen. Sollten die Zeitabstände für die Verarbeitung des Eingangs(-signals) t_i , der Berechnungen t_c und der Ausgabe des Ausgangs(-signals) t_o schneller als benötigt erfolgt sein, werden Wartezeiten t_w eingeführt.

$$t_i + t_c + t_o + t_w = t_s \quad (1)$$

Sind diese Anforderungen erfüllt, spricht man von Echtzeitsystemen. Wird die Dauer t_s überschritten, ist die Echtzeitanforderung verletzt und das Verhalten der Hardware weniger aussagekräftig, da die Signale nicht mehr denen der Realität entsprechen. Bei Systemen, welche in regelmäßigen Abständen ein Kontrollsignal erwarten, kann dies zu einem kompletten Ausfall führen.

Im Projekt dtec emob wird ein Echtzeitsimulator von OPAL-RT benutzt. Dieses hat die benötigten Ein- und Ausgangs-Wandler integriert und bietet eine breite Auswahl an Schnittstellen und Protokollen für spätere Erweiterungen der PHIL-Testumgebung.

Als zu untersuchendes Netz, dargestellt in ABBILDUNG 3, wurde ein Teil des in [1] beschriebenen Kerber-Referenznetzes [2] gewählt und auf das Hamburger Niederspannungsnetz angepasst. Der implementierte Teilstrang beinhaltet einen 20 kV / 0,4 kV-Transformator und fünf Lastabgänge mit jeweils zwei Haushaltsanschlüssen pro Abgang. Die Lastkurven entstammen dem „UMass Smart* Microgrid dataset“ [3]. Die verbindenden Kabelleitungen zwischen Transformator und Hausanschluss entsprechen den in Hamburg verwendeten Ausprägungen. Am zweiten Abgang wird eine Ladestation modelliert, welche mit dem digitalen Zwilling kommuniziert. Der Power-Hardware Teil mit der „realen“ LIS ist am fünften Abgang angebunden.

Die Auswahl des beschriebenen Netzmodells erfolgte aufgrund einer effizienten Fehlererkennung und -behebung. Mit dem am transformatorfernsten Netzabgang angeschlossenen Power-Hardware Teil können Netzrückwirkungen sichtbar gemacht werden. Der Leistungsverstärker wird dabei mithilfe von Glasfaserkabeln angesteuert.

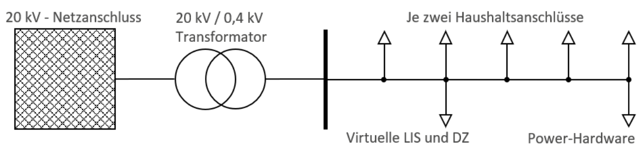


ABBILDUNG 3: VERWENDETES NETZMODELL NACH [2] UND [1].

Wie in Gleichung (1) beschrieben erfolgt in jedem Simulationsschritt die Auswertung der an den Eingängen anliegenden Messwerten sowie deren Übertragung in das Netzmodell, die Berechnung des Netzzustandes und die Ausgabe der benötigten Daten an den Leistungsverstärker und die Netzsteuerung.

B. Power-Hardware

Um leistungsbedürftige Komponenten wie LIS unter Realbedingungen zu erproben, werden HIL-Simulationen um einen Power-Hardware-Bestandteil erweitert. Um die Funktion der Komponenten unter verschiedenen Versorgungsbedingungen testen zu können, wird üblicherweise eine steuerbare Strom- und Spannungsquelle, welche die Umgebungsbedingungen nachstellt, verwendet. Diese hat gegenüber der direkten Verbindung mit dem Verteilnetz die Vorteile der zusätzlichen Absicherung in Fehlerfällen für Netz und Komponenten und dient einem erweiterten Personenschutz. Zudem entsteht die Möglichkeit die Strom- und Spannungsformen präziser einzustellen und vorzugeben.

In der technischen Umsetzung derartiger Systeme wird meist zwischen zwei Verstärkerkonzepten unterschieden: Linearverstärker und Switched-Mode-Power-Amplifier (SMPA). Linearverstärker basieren auf MOSFETs, welche im linearen Bereich der Strom-Spannungs-Kennlinie betrieben werden. Damit kann eine sehr schnelle und präzise Verstärkung erreicht werden. Problematisch sind die bauartbedingt hohen Leistungsverluste, die in Form von Wärme abgeführt werden müssen. Im Gegensatz dazu basieren SMPA auf dem von Schaltnetzteilen (Switched-Mode-Power-Supplies) bekannten Prinzip. Die gewünschte Spannung wird durch das Schalten (leitend / nichtleitend) von mehreren Halbleitern erzeugt. Die durch die Schaltvorgänge verzerrt erzeugte Spannungskurve muss zur Darstellung einer sauberen Sinusform mithilfe von Filtern geglättet werden. Dieser Aufbau erzielt einen höheren Wirkungsgrad, führt jedoch zu ungenaueren und langsameren Ausgaben.

Im Projekt dtec emob wird aktuell ein Linearverstärker für dynamische Netzzustände bei geringen Leistungen genutzt. Hieran wird eine AC-Wallbox angeschlossen, welche wiederum verschiedene Elektroautos laden kann. Damit können die Netzrückwirkungen der verschiedenen Ladearten untersucht werden.

C. Digitale Zwillinge

Digitale Zwillinge (DZ) werden in vielen Anwendungsgebieten mit unterschiedlichen Spezifikationen und Funktionen eingesetzt. Häufige Anwendungen liegen in der Produktion und dem Systemdesign, der Luftfahrt und der Medizin [4]. Die Ziele sind dabei von den jeweiligen Anwendungsgebieten abhängig. Oft soll das Verhalten eines Systems bestimmt und unter verschiedenen Bedingungen vorhergesagt werden, wie zum Beispiel der Energieverbrauch eines Elektroautos [5].

Aufgrund der Vielfalt der Anwendungsbereiche und Forschungsarbeiten existieren eine Vielzahl unterschiedlicher Definitionen des Begriffs der digitalen Zwillinge [4], [6]. Häufig wird die Definition der Defense Acquisition University in Virginia (USA) genutzt [7]. Dabei wird der digitale Zwilling als eine Simulation eines realen Systems, welches Sensorinformationen und Eingangsdaten verwendet um das Verhalten über die Lebensdauer zu bestimmen definiert.

Hieraus resultieren zwei zentrale Bestandteile eines digitalen Zwillings:

- Ein digitales Modell eines entweder existierenden oder eines geplanten Systems.
- Die Kopplung des digitalen Zwillings mit einem physischen System durch Messwerte, sowie die Verwendung dieser Werte zur Aktualisierung des Modells.

Nach [6] ist der Einsatz von digitalen Zwillingen vor allem für Systeme geeignet, deren Verhalten sich während des Lebenszyklus verändert, sodass neue Modelle benötigt werden. Für etwaige Modellaktualisierungen sollten diese Veränderungen anhand der Messungen erkennbar sein.

In dtec emob werden digitale Zwillinge für die Integration verschiedener Elektromobilitätsträgern sowie deren Ladeverhalten in ein gekoppeltes Verkehrsraum- und Energiemodell verwendet. Die zeitlichen Veränderungen im Lebenszyklus sind vor allem anhand der Energieverbräuche und Ladevorgänge sichtbar. Einflussfaktoren sind unter anderem die Batteriealterung, die Umgebungstemperatur, das Kundenverhalten und Softwareeinstellungen.

Zur Modellaktualisierung werden die Messwerte der Lade- und Entladeleistungen, des Ladezustands („State of charge“ SOC) und des Gesundheitszustands („State of health“ SOH) des physischen Fahrzeugs verwendet.

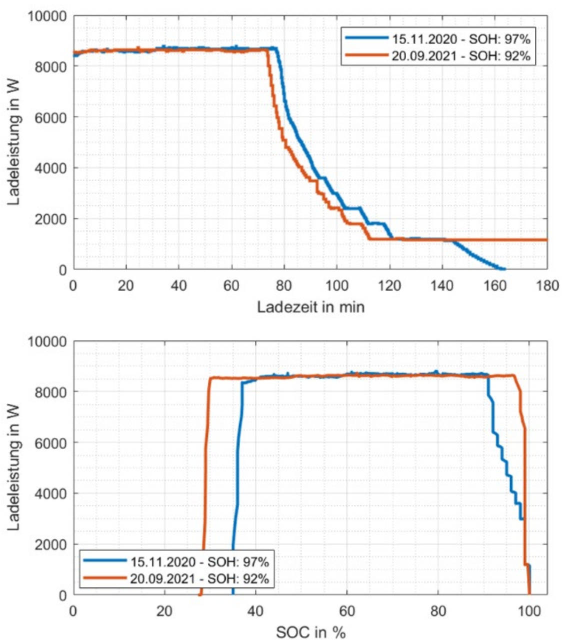


ABBILDUNG 4: VERGLEICH VON ZWEI LADEKURVEN EINES RENAULT ZOE IM ABSTAND VON ETWA 10 MONATEN [8].

ABBILDUNG 4 zeigt beispielhaft die Veränderung der Kurvenform zwischen zwei Ladevorgängen eines Renault ZOE im Abstand von etwa 10 Monaten [8]. In der oberen Grafik ist bei beiden Ladevorgängen zum Zeitpunkt $t = 0$ ein SOC von 45 % erreicht. Die untere Grafik zeigt die Ladeleistung in Abhängigkeit des SOCs. In beiden Plots sind Verschiebungen der Ladeleistungen und der gesamten geladenen Energie erkennbar. Diese sind unter anderem durch die unterschiedlichen SOH zu erklären, welche zur Reduzierung der verfügbaren Kapazität und zu erhöhten Verlusten führt.

Bei einer üblichen Auslegung der Batterie auf 160 000 km bzw. auf acht Jahre [9] sind größere Verschiebungen zu erwarten. Diese führen zu Abweichungen zwischen dem physischen System und dem digitalen Modell. Anhand der auf Messwerten basierenden Aktualisierungen sollen diese Abweichungen minimiert werden.

In einer ersten Umsetzung wird das Modell des digitalen Zwillings auf einem Mikrocontroller mithilfe der zweigeteilten Ladekurve in Gleichung (2) und (3), basierend auf [10], implementiert. Die Kurve ist abhängig von der Ladezeit t, dem SOC, dem Ladezustand zu Beginn SOC_0 und dem SOC_{UP} des Ladeumschaltpunkts, an dem das Ladeverfahren von einem konstanten Leistungsbezug in den konstanten Spannungsbezug wechselt. Die Parameter a und b werden mithilfe der Ausgleichsrechnung in Matlab bestimmt.

$$P(SOC) = \begin{cases} a, & SOC \leq SOC_{\mathrm{UP}} \\ a \cdot \mathrm{e}^{\mathrm{b}\cdot(SOC_{\mathrm{UP}} - SOC)}, & SOC > SOC_{\mathrm{UP}} \end{cases} \quad (2)$$

$$SOC(t) = SOC_0 + \int_{t_0}^{t} P(t)\, dt \quad (3)$$

Die Kommunikation der DZ mit der Simulatorseite des PHIL-Systems erfolgt analog zu der Kommunikation einer AC-Ladesäule mit einem Elektroauto. Der Simulator gibt an einem digitalen Ausgang ein PWM-Signal aus, welches den maximal zulässigen Ladestrom der Ladesäule vorgibt. Über ein zweites PWM-Signal übergibt der Mikrocontroller den Wert der verwendeten Ladestromamplitude an den Simulator.

Im weiteren Verlauf des Projektes soll eine umfangreiche Untersuchung des Einflusses verschiedener Parameter auf die Ladekurve durchgeführt werden, um das bestehende Modell zu erweitern und messwertbasierte Aktualisierungen nach dem beschriebenen Konzept des digitalen Zwillings einbinden zu können.

D. Netzsteuerung

Die Netzsteuerung erhält je nach Auslegung und Funktionsumfang Informationen über den Netzzustand und aktuelle Parameter aus der simulatorseitigen Netzberechnung. Bei Übereinstimmung mit dem hinterlegten Reglungskonzept gibt diese ein Steuersignal an die LIS, die das Signal beziehungsweise die verringerte Ladeleistung an das Auto weitergibt.

Wie in der Einleitung beschrieben, stellt die Entwicklung eines KI-basierten Energiemanagementsystems eine der Hauptaufgaben des Projekts dtec emob dar. Ein erster Ansatz [1] basiert auf der KI-Methodik des „Reinforcement Learning“. Dabei wird die Ladeleistung im gesamten System mittels eines Agenten, welcher über eine anreizbasierte Rewardfunktion eine Maximierung des Zielwerts erreichen soll gesteuert. Mithilfe einer, in einem umfangreichen Trainingsprozess wiederholt durchgeführten, Simulation sammelt der Agent Erfahrungswerte, welche für die Steuerung genutzt werden.

Die beschriebene Methodik liefert insbesonde bei großen Netzen, für die aufgrund des komplexen Systems keine trivialen Steuerregeln aufgestellt werden können, gute Ergebnisse. Das in diesem Bericht betrachtete Netz, ohne dezentrale Erzeuger und bidirektionale Energiespeicher, benötigt im ersten Schritt keine derartige Steuerung. Die für die Erweiterung nötigen Schnittstellen und Kommunikationswege sind bereits vorbereitet und hinterlegt.

III. AKTUELLER STAND

ABBILDUNG 5 zeigt einen Versuchsaufbau bestehend aus dem Echtzeitsimulator und dem PHIL-Teil mit einem Netzgenerator und einer angeschlossenen AC-Wallbox.

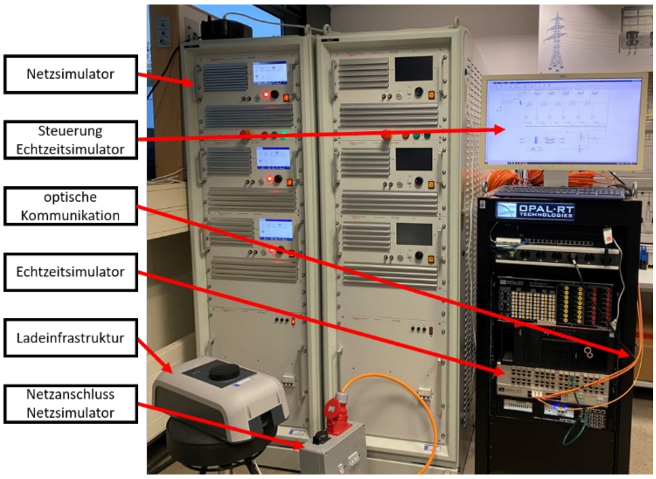


ABBILDUNG 5: VERSUCHSAUFBAU DER PHIL-TESTUMGEBUNG.

In ABBILDUNG 6 sind beispielhaft die Gesamtleistung des simulierten Netzes, die Ladeleistung des modellierten Elektroautos und die resultierende Spannung am letzten Knoten, die von dem Netzsimulator ausgegeben werden kann, dargestellt. In dem gewählten Netz ist die Leistung des Ladevorgangs deutlich erkennbar. Wie zu erwarten verhält sich die Spannung gegenproportional zu den Leistungen, da durch die in den Verteilkabeln fließenden Ströme Spannungen abfallen.

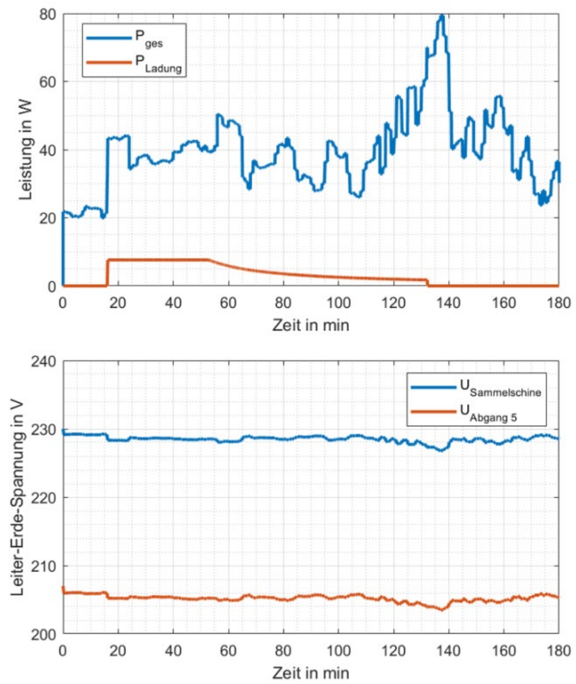


ABBILDUNG 6: GESAMTLEISTUNG, LADELEISTUNG MODELLIERTES ELEKTROAUTO UND SPANNUNG AM LETZTEN NETZANSCHLUSSPUNKT.

Um den Projektstand des PHIL-Gesamtsystems in Bezug auf den aktuellen Entwicklungsstatus einschätzen zu können, sind die einzelnen beschriebenen Aufbauten anhand des Technologiereifegrades in TABELLE I eingestuft. Es wird eine durch den Projektträger Jülich modifizierte Definition [11], basierend auf den Grundlagen der DIN ISO 16290 [12], verwendet. Die neustufige Definition des TRL verwendet die nachfolgenden Definitionen:

- TRL 1: Beobachtung und Beschreibung des Funktionsprinzips
- TRL 2: Beschreibung des Technologiekonzepts und/oder der Anwendung einer Technologie
- TRL 3: Nachweis der Funktionstüchtigkeit einer Technologie, „Proof of Concept“
- TRL 4: Versuchsaufbau im Labor
- TRL 5: Versuchsaufbau in Einsatzumgebung
- TRL 6: Prototyp in Einsatzumgebung
- TRL 7: Prototyp im Einsatz
- TRL 8: Qualifiziertes System mit Nachweis der Funktionstüchtigkeit im Einsatzbereich
- TRL 9: Qualifiziertes System mit Nachweis des erfolgreichen Einsatzes

TABELLE I: TECHNOLOGISCHER REIFEGRAD DER PHIL-BESTANDTEILE NACH [11].

Aufbau / Programmierung	*Technologischer Reifegrad*
Netzmodell	TRL 4
Simulatorischer PHIL Teil	TRL 4
Kommunikation	TRL 3
Digitaler Zwilling	TRL 3
Netzsteuerung	TRL 3
Power-Hardware Teil	TRL 4
Gesamtaufbau (Minimum der Einzelkomponenten)	TRL 3

IV. AUSBLICK AUF ZUKÜNFTIGE ERWEITERUNGEN

Im weiteren Projektablauf sind umfangreiche Erweiterungen für das PHIL-System geplant:

- Da das Projekt auf die Hamburger Metropolregion ausgerichtet ist, sollen zukünftig größere, in Hamburg typische Verteilnetzstrukturen untersucht werden. Es kann eine größere Anzahl von Verbrauchern integriert werden und die Auswirkungen des Hochlaufs der Elektromobilität auf die weiteren Netzbestandteile detaillierter analysiert werden.
- Mithilfe des beschriebenen Konzeptes sollen digitale Zwillinge von verschiedenen Elektromobilitätsträgern entstehen. Dafür werden Modelle aufgebaut und geeignetes Messequipment in den Mobilitätsträgern installiert.
- Durch das größere betrachtete Netz wird die benötigte Netzsteuerung komplexer und die beschriebenen Steuersysteme können integriert werden. Dafür soll auf einem Mikrocontroller eine entsprechende Steuerung implementiert werden.
- Um statische Netzzustände und hohe Leistungen abdecken zu können, soll der Power-Hardware-Teil um mehrere SMPA-Systeme erweitert werden. Mithilfe von getrennten Netzsimulatoren und daran

angeschlossenen Verbrauchern soll ein dezentrales System entstehen.

- Im Power-Hardware-Teil sollen haushaltstypische elektrische Leitungen in das dargestellte Microgrid integriert werden. Auf diese Weise können die Auswirkungen von Ladevorgängen auf weitere Haushaltslasten und die Wechselwirkungen im Bereich V2H realistischer dargestellt werden.
- Lokale Energiespeicher und Erzeuger sowie deren Auswirkungen auf elektromobile Ladekurven und den Energieverbrauch der Haushalte sollen mit Hilfe von einem PV-Simulator und einem PV-Batteriespeicher abgebildet werden. Die genannten Komponenten können über Wechselrichter in das Microgrid einspeisen bzw. im Fall des Speichers geladen werden.
- Mithilfe einer steuerbaren Klimakammer sollen die Auswirkungen von Temperatur und Luftfeuchtigkeit auf LIS und EMT im Einsatz untersucht werden.

Durch den modularen Aufbau und die Möglichkeit einzelne Bestandteile für spezifische Experimente hinzuzufügen bzw. zu entfernen, sind zusätzliche Erweiterungen möglich. Die Umsetzung ist abhängig von der Datenverfügbarkeit und von der weiteren Ausrichtung der Forschungsschwerpunkte.

DANKSAGUNG

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt dtec emob].

LITERATUR

[1] Y. Fu et al., (in Druck), „AI-based charging management for the integration of electric vehicles using a reference low voltage grid in Hamburg,“ *Conference on Sustainable Energy Supply and Energy Storage Systems,* 2022.

[2] G. Kerber, „Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen,“ Technischen Universität München, München, 11.10.2010.

[3] S. Barker, A. Mishra, D. Irwin, E. Cecchet, P. Shenoy und J. Albrecht, „Smart*: An Open Data Set and Tools for Enabling Research in Sustainable Homes,“ *Proc. SustKDD.,* 2012.

[4] B. R. Barricelli, E. Casiraghi und D. Fogli, „A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications,“ *IEEE Access,* Bd. 7, p. 167653–167671, 2019.

[5] Z. Zhang, Y. Zou, T. Zhou, X. Zhang und Z. Xu, „Energy Consumption Prediction of Electric Vehicles Based on Digital Twin Technology,“ *World Electric Vehicle Journal,* Bd. 12, Nr. 4, p. 160, 2021.

[6] L. Wright und S. Davidson, „How to tell the difference between a model and a digital twin,“ *Advanced Modeling and Simulation in Engineering Sciences,* Bd. 7, Nr. 1, 2020.

[7] Defense Acquisition University, *Glossary of Defense Acquisition Acronyms and Terms,* Virginia.

[8] *(unveröffentlicht). Ladedaten verschiedener Elektroautos.*

[9] W. Rudschies, „Elektroauto-Batterie: Lebensdauer, Garantie, Reparatur,“ 2022. [Online]. Available: https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/info/elektroauto-batterie/. [Zugriff am 1 9 2022].

[10] F. Heider et al., (in Druck), „A generic EV charging model extracted from real charging behaviour".

[11] Projektträger Jülich, *Definition des Technologischen Reifegrades (in Anlehnung an die TRL.*

[12] *DIN ISO 16290:2016-09, Raumfahrtsysteme_-Definition des Technologie-Reifegrades_(TRL) und der Beurteilungskriterien (ISO_16290:2013),* Berlin, 2016.

Reinforcement learning based charging management for electric vehicle fleet to reduce transformer overloading in distribution networks

Yuzhuo Fu*, Detlef Schulz
Electrical Power Systems
Helmut Schmidt University / University of the Federal Armed Forces Hamburg
Hamburg, Germany
*yuzhuo.fu@hsu-hh.de

Dennis Salvador Versen*, Marcus Stiemer
Theory of Electrical Engineering and Numerical Simulations
Helmut Schmidt University / University of the Federal Armed Forces Hamburg
Hamburg, Germany
*versend@hsu-hh.de

***Abstract* – With the widespread integration of electric vehicles (EV) in distribution networks (DN), the distribution network operator faces new challenges. Uncontrolled charging processes of a large amount of EVs can result in many problems in power grids such as power quality issues and transformer overloading. Recently, many model-free methods based on Reinforcement Learning (RL) are proposed for EV charging management, which finds the optimal policy through the interaction between agent and environment. This paper investigates the performance of the RL-based EV charging management on relieving transformer overloading with finer measurement data (1-minute resolution) comparing the previous work with 15-minutes resolution. In addition, the states of the system in the past 5 minutes are sent together to the agent for a better perception of the future dynamics. The simulation results show that the proposed charging strategy works well with finer time resolution.**

Keyword* – *charging management, reinforcement learning, electric vehicle, time resolution

NOMENCLATUR

DN	Distribution Network
DQN	Deep-Q-Network
EV	Electric Vehicle
MDP	Markov Decision Process
RES	Renewable Energy Resource
RL	Reinforcement Learning
SOC	State of Charge
V2G	Vehicle-to-Grid
PV	Photovoltaic
s_t	state of the system at the time t
Λ_t	transformer load ratio
$P_{\mathrm{H},t}$	cumulated load of all households
$P_{\mathrm{EV},t}^{\max}$	cumulated charging demand of EVs
$E_{\mathrm{EV},t}$	cumulated energy requirement of EVs
T_{id}	intraday time index
a_t	charging factor decided by the agent
$P_{\mathrm{EV},t}$	cumulated charging power of EVs
r_t	reward at the time t
$r_{\Lambda,t}$	penalty term in the reward function
$\Lambda_{\max}$	threshold of the transformer loading
$\overline{A_{\mathrm{EV}}}$	average charging factor
$\bar{\Lambda}$	average transformer loading
N_Λ	number of threshold violation of the transformer limit
E_{fail}	unsatisfied energy demand of EVs

I. INTRODUCTION

The use of fossil fuels creates many environmental problems. The Intergovernmental Panel on Climate Change has found that emissions from fossil fuels are the dominant cause of global warming [1]. Germany produced 762 million tons of carbon dioxide in 2021, a share of roughly 30 % comes from power sector and 20 % is caused by transport sector [2]. From the perspective of electricity generation, the integration of RES like wind and photovoltaic systems produced about 225 TWh electricity energy in 2021 and the share of renewables in the public net electricity generation is about 45.7 % [3]. In contrast to the electricity generation, the change on electricity consumption side is much slower, especially in the transportation sector. The share of renewables rose to 6.8 % in regards to transport in Germany but the main contribution comes from biofuels not the directly use of clear electricity from renewable energy resources (RES) [4]. Nowadays, the share of electric and hybrid cars reaches nearly 50 % (full-EV 14 %, hybrid-EV 29 %) in all new registrations [5]. However, it will take a long time to retire the large number of traditional cars and increase the overall share. The widespread integration of EV can affect the power grid in a negative way, such as the significant reduction in the system's power quality and overloads in the distribution lines and transformers. Van der Burgt [6] found that a transformer overload can be observed at a low EV penetration level of 25 % with simultaneous charging. For this purpose, a charging strategy to cooperate the charging processes of EV fleet is needed.

https://doi.org/10.24405/14530

Some optimization methods have been proposed for the cooperative charging in the literature such as dynamic and stochastic programming. The biggest disadvantage of optimization-based methods is that accurate models are required to describe charging behaviour, energy demand and available flexibility [7]. However, the user behaviour is a random process, whose patterns are affected by a variety of uncertain factors such as family structure, income status, location and weather. Exact modelling of each individual user is nearly impossible. Nowadays, model-free approaches based on reinforcement learning have achieved great success in complex decision-making applications. The advantage of RL in Sequential Decision-Making problem can be summarized as the follows. The ability to learn the pattern and dynamics of stochastic processes through historical data avoids complex modelling of uncertain factors and makes the training process in a model-free way. In addition, a RL-agent after training can response to dynamic environment in real-time, which would be difficult for traditional optimization approaches in a large and complex system. Recently, many works related to RL-based charging management for EV fleets can be found in literature. In [8], a coordinated EV charging based on a policy gradient algorithm aiming to smooth out the load profile of a parking lot is proposed. In [9], a soft-actor-critic based method in combination with nodal multi-target characterization is proposed to schedule of large-scale EV in DN.

In this work, an intelligent charging management based on reinforcement learning, which is first presented in the previous paper [10] will be further developed. In order to manage the charging processes of EVs in a residential area, the objective is to satisfy the charging demands of end users as quickly as possible without exceeding the threshold given for transformer loading. Concretely, the RL-agent receives data from meters installed on the transformer and charging points and then sends a control signal to limit charging power. The system is dynamic due to the uncertainty of user power consumption and EV mobility behaviour. Then, the agent tries to take the optimal charging control in order to maximize the benefits of the entire system. The contribution of this work can be summarized as the follow. At first, finer time interval in the RL-environment is considered for the purpose to better modelling of dynamic of user behaviours. In order to investigate the impact of time interval on the performance of RL-agent, the simulation results for 1-minute and 15-minutes time steps are compared with each other. In addition, inspired by some applications of RL like Atari Breakout [11], the state of the past few time steps are also considered aiming to better reflect the trend of the system. The effects of these two improvements will be shown by comparison between different configurations and scenarios.

This paper is organized as follows: the whole system with assumptions and the mathematical description of the EV charging problem are presented in Section II. The RL algorithm and training process based on real world data is introduced in Section III. Then, a case study and the simulation results including comparison are shown in Sections IV and V. Finally, Section VI summarizes the paper.

II. MATHEMATICAL DESCRIPTION OF THE EV CHARGING PROBLEM

In this paper, we consider a DN in low voltage level, in which EVs belonging to private households need to be charged in a residential area. All EVs can only be charged at this area, the multi-location charging is not considered yet. Bidirectional charging (V2G) takes advantage of the storage capacity of the EV battery to relieve the imbalance between local electricity production and electricity consumption. The aim of this paper is firstly to avoid the overloading or reduce the loading of transformers in order to integrate more DERs or EVs in DN. So only the unidirectional charging is allowed in our assumptions, which is possible to be implemented within a shorter amount of time, than V2G applications. Furthermore, some typical DERs like photovoltaics are not considered in the simulation even through more and more private PV systems can be found in DNs. The reason is, the uncertainty of the system contains the load profiles of households and the mobility behaviours of EVs. If a RL-agent handles the dynamic and uncertainty of this system well, it can also in principle response to the additional randomness of photovoltaics.

The EV charging management developed in this work is a centralized control system, in which a communication among distribution network operator, EV users and RL-agent is necessary. The communication network is bases on a naive assumption regardless of privacy protection and availability of metering equipment. Firstly, the RL-agent is able to receive the measurement data at the level of transformer such as the current loading of the transformer. In addition, the usage data at the customer level like the load profile of households and the charging data of EVs are also send to the RL-agent. This is worth to noting that the information at customer level is at first aggregated and then send to the agent, which means the charging management only knows the cumulative value of the loads but not the measurement data of each household and EV. The advantage of such a communication system is that the dimensionality of input data is significantly reduced to an aggregated level, which makes the training process faster. The major disadvantage is that the centralized charging management is not able to control the charging process at an individual level in regard to the preference of each user.

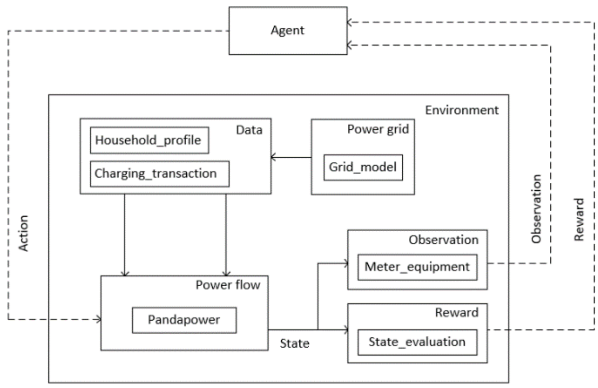


FIGURE 1: SIMULATION ENVIRONMENT [10].

The aim of the RL-agent is to satisfy the charging demands of end users as quickly as possible without exceeding the threshold given for transformer loading. The agent can receive the current information on the transformer and usage data at the aggregated customer level. The biggest challenge is that the agent is disable to predict the future user behaviour so a learning process is needed to capture the pattern of electricity consumption and mobility mode. For this reason, a reinforcement learning based EV charging management is used, which aims to maximize the future cumulative rewards through taking an optimal action according to the current state of system. The RL-agent developed in another work [10] is the basis of this paper, in which the definition of a Markov Decision Process (MDP) and the mathematical description of the entire system are introduced in detail. The environment built to train the RL-agent for EV charging management is shown in FIGURE 1. In following part, only the most important components of the MDP will be introduced.

The state space is the set of values obtained from measurements or provided actively by end-users. In the environment, the state s_t at time step t is described:

$$s_t = \{\Lambda_t, P_{\mathrm{H},t}, P_{\mathrm{EV},t}^{\max}, E_{\mathrm{EV},t}, T_{\mathrm{id}}\} \quad (1)$$

Λ_t defines the transformer load ratio caused by the load of all feeders and cable losses. $P_{\mathrm{H},t}$ presents the cumulated load of all households. T_{id} is the intraday time index used to reflect temporal relevance of the environment. $E_{\mathrm{EV},t}$ is the cumulated energy requirement of all EVs and $P_{\mathrm{EV},t}^{\max}$ is the cumulated charging power demand of all EVs which is dependent on the individual state of charge (SOC) of the EV or the customer preference.

The action space consists of all possible control signals of the RL-agent. In this MDP, the action a_t at time step t is modeled as a factor that determines the acceptable EV charging power by multiplying it with the desired charging demand $P_{\mathrm{EV},t}^{\max}$:

$$P_{\mathrm{EV},t+1} = a_t P_{\mathrm{EV},t}^{\max} = \sum_{i=1}^{N_{\mathrm{EV}}} a_t P_{\mathrm{EV},i,t}^{\max} \quad (2)$$

In order to keep the dimension of the action space within a reasonable range, we discretized the charging factor a_t into 6 stages: 0, 0.2, 0.4, 0.6, 0.8, 1. The reward function r_t is used to evaluate the effectiveness of a_t in the state s_t in MDP, it is formulated as follows:

$$r_t = a_t \cdot 5 + r_{\Lambda,t} \quad (3)$$

$$r_{\Lambda,t} = \begin{cases} -200 & \text{if } \Lambda_t > \Lambda_{\max} \\ 0 & \text{else} \end{cases} \quad (4)$$

$a_t \cdot 5$ indicates that the RL-agent seeks to provide the maximum charging power at all time steps so that the energy demand of EVs can be satisfied as soon as possible. $r_{\Lambda,t}$ is defined as a penalty term, once the prescribed threshold of the transformer loading $\Lambda_{\max}$ is exceeded. In this work, $\Lambda_{\max}$ is set to be 70 % according to the base-load, which will be explained in chapter V.

III. REINFORCEMENT LEARNING ALGORITHM

The state transition probability of the above environment is difficult to be accurately modelled due to the high uncertainty of many factors such as the load profiles and mobility behaviour of end users. On this account, a well-known model-free reinforcement learning algorithm deep Q-network (DQN) is used to solve the build MDP. The configuration of the DQN and the correspondent training process can be found in the work [10]. DQN is easy to implement and can show a high efficiency in small observed spaces with discrete action spaces even though they converge slow. Instead of using a Q-Table like in Q-Networks the DQN-Algorithm uses a neural network to predict the action outcome in specific states, which causes the best reward gain in the current step just as in the future steps. Similar to the MDP an adapted Bellman-Equation is used to update the neural network. Instead of the discounted retracted future reward, the discounted next step which recursively contains the assumable future reward is used go estimate the score in the future.

As mentioned above a realistic estimation of the behaviour of the load curve is hard to give due to many volatile factors. For this reason, mathematic models often fail or give just a vague proximation of the reality. RL-Algorithms are able to see patterns in the history of load profiles. Thus, one idea is to take the past observation spaces into account. The information through the feedback of the past observed states can help to derive the optimal charging factor for the next timestep without knowing the future state. One advantage of this method is that the agent can react without knowing the income of new loading inquiries. That makes it easier to implement the agent to the real world. According to that, our state is not only a depiction of the status quo but rather a time series of the last observed states.

$$\boldsymbol{S_t} = \{s_t, s_{t-1}, s_{t-2}, \ldots, s_{t-n}\} \quad (5)$$

The factor n will define how far in the past the states will be considered. One object for this work is to regard different n´s to see how this will make an impact on the performance of the agent.

IV. CASE STUDY

A. Grid Model

The benchmark network CIGRE Testbench LV is used in this paper as a test system, which was specially developed for the investigation of integration of DERs in DNs [12]. This network model in a residential area consists of 18 buses, 85 household loads and 17 lines, which is fed by a single 400 kVA, 20 kV / 400 V transformer. The aim of the simulation is not to test the EV charging management system with many different scenarios regards to the EV penetration level but to investigate the performance of charging management with finer time step and past information, so we consider a fixed number of charging points in this area. A total of 60 private charging points is allocated to the 85 households, which means about 70 % EV penetration level.

B. Data Preparation

The RL-agent is trained on a real-world power usage dataset consisting of household load profiles and EV charging transactions. The load data of households is taken from the UMass Smart Dataset, which collected power consumption of 114 single-family apartments for three years [13]. The home EV charging transactions are collected from Electric Nation with nearly 700 EV owners taking part in an 18-month trial, which records the charging station ID, arrival time, departure time and consumed energy during the session [14]. Both data banks collected usage profiles in 1-minute interval. The finer measurement data makes the performance comparison of RL-agent with different time intervals possible.

C. Performance metrics

This paper uses the following four performance metrics, which are proposed in our previous work [10] , to evaluate the RL-based charging management system: average charging factor $\overline{A_{\mathrm{EV}}}$, average transformer loading $\bar{\Lambda}$, N_Λ is the number of threshold violation of the transformer limit $\Lambda_{\max}$ and E_{fail} represents the amount of unsatisfied energy demand.

D. Simulation Setup

In order to investigate the impact of time interval on the performance of charging management, the RL-agent is trained with two different time resolution: 15-minute and 1-minute. The original configuration of the simulation (called the first scenario) depends on 15-minute time interval with feedback of only the current state, which corresponds to the configuration of our work [10]. Theoretically, the finer measurement data show more dynamic information, which is useful for the agent to learn the user's power consumption pattern and even better predict the trend. Considering the fineness of available data, both the second and the third scenario of the simulation setup are based on the 1-minute resolution while the third scenario observes all states of the past 5 minutes. As a result, there are a total of three different configurations of the simulation setup, which can be seen in TABLE Ⅰ.

TABLE Ⅰ: THREE SCENARIOS OF THE SIMULATION SETUP.

Scenario	Simulation Setup	
	Time Resolution	***Feedback of the past information***
1	15-minute	No
2	1-minute	No
3	1-minute	Yes

Although the full year of usage profiles are available in the data bank, the training data is defined only as the power consumption of the households and EV charging transaction for the month January. The main reason is the calculation burden especially for the simulation with 1-minute time resolution, which results in 525.600 time steps for a year-long simulation. The power consumption data in February is chosen as the test data to evaluate the performance of the charging algorithm. The environment is built on basis of OpenAI Gym and the RL-agent is implemented using TensorFlow.

V. SIMULATION RESULTS

E. Uncontrolled charging

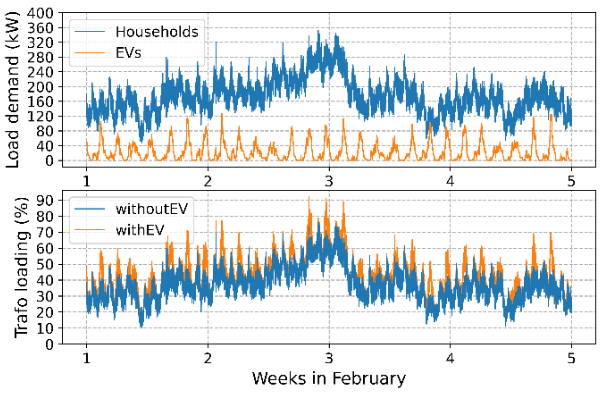


FIGURE 2: LOAD DEMAND AND TRANSFORMER LOADING WITH UNCONTROLLED CHARGING IN FEBRUARY.

It is worth to show the transformer loading and charging profiles of EVs without any management at first. Then, the effectiveness of the RL-based charging management can be better evaluated. The impact of 60 EVs can be seen in FIGURE 2 where the simulation results for February are displayed and charging coincides with peak household consumption at many time steps. The accentuated peak load leads to around 10 %-20 % increase in transformer peak loading compared to the base load without EVs. In contrast to our previous work [10], the usage pattern is more difficult to be captured because of a large load variance. In addition, the peak load caused by households at some time steps exceeds the defined threshold of the transformer loading $\Lambda_{\max}$. That will result in the agent being penalized for any action it took, which brings great challenge to the training of the agent.

F. The impact of finer measurent data on the performance

Limited by computational power, we only train 5 agents for each setting in the TABLE Ⅰ. Then the agent with the best performance among them is chosen to compare with each other. Before comparing the performance of agents with different time resolution, the performance improvements compared to uncontrolled charging are first evaluated (see TABLE Ⅱ). The impact of the two trained agents with 15-minute (the first scenario) and 1-minute (the second scenario) time resolution respectively on the transformer loading is shown in FIGURE 3. It shows that some load peaks in the both scenarios are reduced but the behaviours of both agents are not same.

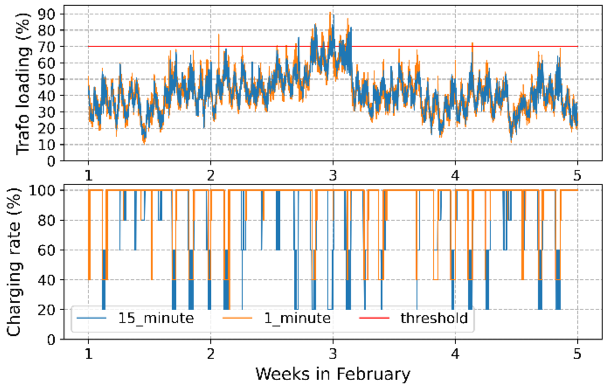


FIGURE 3: IMPACT OF AGENTS WITH DIFFERENT CONFIGURATIONS REGARDING TO THE TIME RESOLUTION ON TRANSFORMER LOADING AND THE CHARGING RATE.

It is noticeable that the load variance of the scenario with 1-minute resolution is much larger than the scenario with 15-minute resolution. The reason would not be the agent's policy but more likely the finer measurement data itself. It can be confirmed that the agent of the second scenario fails at some time steps in regard to the threshold of the transformer loading such as the load peak at the start of the second week. In contrast, the agent of the first scenario seems like to have a better performance in relation to the number of threshold violation of the transformer limit if we ignore that there are more load peaks in the finer measurement data. The both agents can sometimes even limit the transformer load to just around the threshold, which shows that they find the best compromise between satisfying the power demand of EVs and avoiding the transformer overloads. However, if we take the simulation results for the last two weeks with relatively low power consumption into account, the policy of the second agent is closer to optimal. From the FIGURE 3, it can be seen that during the last two weeks the total power consumption is low enough that the EVs are able to be charged with the maximum rate at any time without causing many overloading. For this reason, the behaviour of the second agent is more aggressive and tries to keep the charging rate at a higher value. The policy of the first agent is confusing during this time, in which it always tries to reduce the EV charging rate to a low level even through the current transformer loading is far from the threshold.

TABLE II compares the performance of the two RL-agents using the performance metrics defined in Section IV. Only small differences between the two agents can be observed regards to the average transformer loading $\bar{\Lambda}$ and the number of threshold violation N_{Λ}. Due to the more conservative policy, the average charging factor $\overline{A_{\mathrm{EV}}}$ of the first scenario with 15-minute time resolution deceases by around 4 %. The number of threshold violation of the transformer limit can't be directly compared because of the different time resolution. Therefore, we calculate the mean value of each time block in 15-minute interval in order to unify the time resolution. It is worth noting that significant more failed working points (exceed the limit value 70 %) of the second scenario can be seen in the FIGURE 3 than the number in the TABLE II because of the calculate of mean value for each 15-minute time interval. In terms of the amount of unsatisfied EV energy demand, the index E_{fail} shows that a total of 116 kWh is not successfully charged into all EVs during a month, which accounts for only about 1.8 % of total energy demand of about 14.743 kWh. With almost the same performance on reducing transformer loading, only 83 kWh energy is not successfully charged into the EVs by the second scenario.

TABLE II : COMPARING THE PERFORMANCE OF THE AGENTS WITH DIFFERENT TIME RESOLUTION.

Scenario	Performance Metrics				
	$\overline{A_{EV}}$	$\bar{\Lambda}$	N_{Λ} - 70%	N_{Λ} - 80%	E_{fail}
uncontrolled	100%	42.03%	69	15	0 kWh
1	88.73%	41.98%	48	8	116.1 kWh
2	92.92%	41.85%	46	8	83.1 kWh

In summary, the finer measurement data with more detailed and dynamic information seems like to result in a better performance but it might be caused by the finer measurement data rather than the policy. Due to more frequent interventions, it becomes easier for the agent with 1-minute time resolution to find the compromise between transformer overloading and insufficient energy of EVs. However, the simulation results indicate that both RL-agents converge to a local optimum but not the global optimum.

G. The impact of the past information on the performance

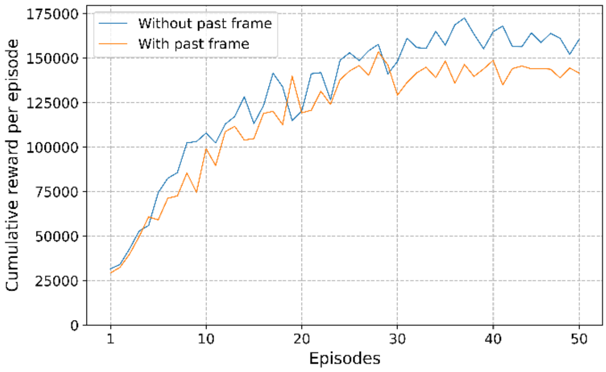


FIGURE 4: CUMULATED REWARD PER EPISODE OF THE TRAINING PROCESSES OF THE SECOND UND THE THIRD SCENARIO.

The states of the past few time intervals contain more dynamic information of the system that principally enables the agent to control the charging rate with more consideration on the possible future states. The training processes of the two scenarios with and without the feedback of states in the past 5 minutes are shown in FIGURE 4. For both scenarios, 5 agents are trained with the same initial conditions and the average cumulative reward per episode is calculated.

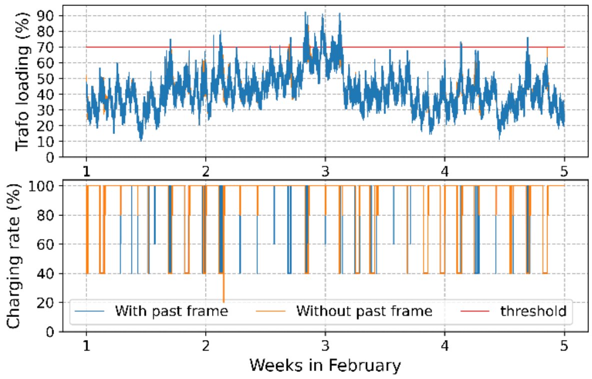


FIGURE 5: IMPACT OF THE AGENTS WITH THE SECOND AND THE THIRD SCENARIO ON THE TRANSFORMER LOADING AND CHARGING RATE.

Unexpectedly, the agent considering the past states do not have a better performance than the agent just observing the current state. In most episodes, the cumulative rewards of the third scenario are lower than the second scenario. In addition, the gap is expanded at the beginning and then stable at a certain value towards the end of the training. It is noticeable that the training curve of the agent with feedback of the past states seems to be stretched along the x-axis, which means it could coverage to a better policy if we increase the training episodes. Similar to the previous chapter, the curve of transformer loading, the charging rate and the corresponding performance metrics are shown in the FIGURE 5 and TABLE III respectively. There is no significant difference between the two scenarios regarding to the average charging factor $\overline{A_{\mathrm{EV}}}$ and the average transformer loading $\bar{\Lambda}$, which means both of them try to keep the charging rate at a high level. However, the more frequent thresholds exceeding N_{Λ} and the larger amount of energy shortage E_{fail} in EVs indicates that the third Agent reduces the charging power not at the optimal moments.

TABLE III: COMPARING THE PERFORMANCE OF THE AGENTS WITH AND WITHOUT THE PAST INFORMATION.

Scenario	Performance Metrics				
	$\overline{A_{EV}}$	$\bar{\Lambda}$	N_{Λ} - 70%	N_{Λ} - 80%	E_{fail}
2	92.92%	41.85%	46	8	83.1 kWh
3	92.48%	41.85%	53	10	101.9 kWh

By comparing the two scenarios, it can be shown that the agent is unable to utilize the past information properly and then track the system dynamics for a better perception. In addition, the past information even negatively affects the agent's decision-making, which makes the training process more difficult and ineffective.

VI. CONCLUSIONS

In this paper, the RL-based EV charging management is further developed, which is proposed in our previous work. A slight improvement on the performance can be seen once the measurement data becomes finer (from 15-minutes resolution to 1-minute resolution). However, the agent can't extract the dynamic information from the past few time intervals for a better performance. The reason might be the definition of the state space (the input layer of neural network). Some external information such as the intraday time index T_{id} restricts the agent's experience to be applied only at that time step, which can't be generalized for the other scenarios. For the future work, a wider range of sensitivity analysis is needed.

From the perspective of the optimization objective, avoid overloading of transformers is not a suitable application to maximize the potential of RL-algorithms. Theoretically, a simple controller is also able to limit the transformer loading, which only needs to calculate the power flow of the grid according to charging power requirement of EVs for the next time step and then reduce the charging rate if needed. The advantage of RL is that it can adjust the current action in a random and unpredictable environment to maximize total revenue over a certain time. For the future work, new challenges such as collective self-consumption and energy management regarding to cost will be considered. In addition, a single control signal applying on all charging stations is not efficient. Each EV customer has its own mobility- and charging behaviour, which needs a customized individual charging management. For this reason, a distributed energy management with multi-agent-system will be developed in the future.

Acknowledgement

This research paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge dtec emob [UT 7001 – Digitalization and E-Mobility].

References

[1] IPCC, „Climate Change 2022-Mitigation of Climate Change," 2022.

[2] „Emissionsquellen," Umwelt Bundesamt, 2021. [Online]. Available: https://www.umweltbundesamt.de/themen/klima-energie/treibhausgas-emissionen/emissionsquellen#energie-stationar.

[3] „Public Net Electricity Generation in Germany in 2021," Frauenhofer, 2022. [Online]. Available: https://www.ise.fraunhofer.de/en/press-media/news/2022/public-net-electricity-in-germany-in-2021-renewables-weaker-due-to-weather.html.

[4] Umwelt Bundesamt, „Erneuerbare Energie im Verkehr," 2022. [Online]. Available: https://www.umweltbundesamt.de/daten/energie/erneuerbare-energie-im-verkehr#:~:text=%E2%80%9EAnteil%20erneuerbarer%20Energien%20am%20%E2%81%A0,wieder%20auf%206%2C8%20%25..

[5] Clear Energy Wire, „Germany reaches one-million electric vehicles target with half a year delay," 2021. [Online]. Available: https://www.cleanenergywire.org/news/germany-reaches-one-million-electric-vehicles-target-half-year-delay.

[6] J. v. d. Burgt, B. Wille-Haussmann und A. N. Andersen, „Grid Impact of Charging Electric Vehicles; Study Cases in Denmark, Germany and The Netherlands," *IEEE Eindhoven PowerTech,* 2015.

[7] N. Sadeghianpourhamami, J. Deleu und C. Develder, „Definition and Evaluation of Model-Free Coordination of Electrical Vehicle Charging With Reinforcement Learning," *IEEE Transactions on Smart Grid,* 2020.

[8] Y. Jiang, Q. Ye und B. Sun, „Data-Driven Coordinated Charging for Electric Vehicles with Continuous Charging Rates: A Deep Policy Gradient Approach," *IEEE INTERNET OF THINGS JOURNAL,* 2021.

[9] J. Jin und Y. Xu, „Optimal Policy Characterization Enhanced Actor-Critic Approach for Electric Vehicle Charging Scheduling in a Power Distribution Network," *IEEE TRANSACTIONS ON SMART GRID,* 2021.

[10] Y. Fu, D. S. Versen und A. Stadler, „AI-based charging management for the integration of electric vehicles using a reference low voltage grid in Hamburg," in *NEIS*, Hamburg, 2022.

[11] Keras, „Deep Q-Learning for Atari Breakout," 2020. [Online]. Available: https://keras.io/examples/rl/deep_q_network_breakout/.

[12] International Council on Large Electric Systems, „Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources," CIGRE, 2014.

[13] UMassTraceRepository, „Smart* Data Set for Sustainability," 2017. [Online]. Available: https://traces.cs.umass.edu/index.php/smart/smart.

[14] Western Power Distribution, „Electric Nation Data," 2022. [Online]. Available: https://www.westernpower.co.uk/electric-nation-data.

Production Next Door – A business model for local, sustainable production

Pascal Krenz*, Lisa Stoltenberg, Dominik Saubke, Julia Markert
Helmut-Schmidt-University
Hamburg, Germany
*info@productionnextdoor.com

Abstract **– In many industries today, the manufacture of products is characterized by global value creation processes based on the division of labour. However, various crises (e.g. global pandemic, trade conflicts, global warming) show us the limits of global production. The risks and emissions of complex, global supply chains, inadequate labour and environmental standards along the value chains or customs barriers are leading to a rethinking in different sectors. Local production offers an opportunity to overcome current and future challenges by reducing cycles of value creation and involving regional actors. Local manufacturing can especially contribute to social, ecological and economic sustainability if it takes three dimensions into account (LM³): production at the place of need, production on site and production using local resources.**

The project "Digital Urban Production" is dedicated to the question of how local production can succeed. At the same time, it tries to develop a business model based on these findings and to implement it in the field of furniture manufacturing for Hamburg with the concept "Production Next Door" (ProNeD). This paper shows how ProNeD's business model aims to promote the path to local production as understood by LM ³.

Keywords – Local Production, sustainable production, business model, production network, Value Creation

NOMENCLATURE

BM	Business Model
SME	Small and medium sized enterprises
ProNeD	Production Next Door

I. INTRODUCTION

Industrial product manufacture today is realized by global value creation processes based on the division of labour. There is no doubt that this form of value creation using local specialization and regional competitive advantages (e.g. lower labour costs) enables cost-efficient production and reliable product availability in many areas. The world is currently facing many ecological, social and economic challenges, with global manufacturing often amplifying them: disrupted global supply chains due to a pandemic or increasing international crises, international trade conflicts, structural impoverishment of regions, insufficient harmonization of labour and environmental protection standards along global value chains.

In many scenarios, the return of product manufacture to the place of demand offers potential for countering the negative effects of global value creation based on the division of labour. The emergence of local markets and the promotion of local production represent a central dimension of the transformation to a circular economy [1]. Local production needs to ensure that regional producers are able to produce a wide range of products to satisfy specific regional demands [2, 3].

Local production can take various forms. In many areas regional clusters exist, which bundle competencies through local value chains and the companies as a whole form a competitive consortium in global markets (e.g. Hamburg Aviation, Life Science Nord). Likewise, global corporations promote forms of local production by performing the final steps of the value chain close to the costumer (e.g. regional product manufacture by Coca Cola). Trades and crafts also represent a form of local production, which individually addresses the needs of customers on site in smaller batches.

The different forms of local production can be described based on the following three dimensions [2]:

(1) **Production at the place of need**

(2) **Utilization of local resources** by implementation of production by local stakeholders and using local (raw) materials

(3) **Addressing of local demands** by producing individualized / locally adapted products on-demand

The gradual implementation of these three design dimensions of local production offers great opportunities for ecologically, socially and economically sustainable value creation in various sectors. **Ecological sustainability** is achieved by reducing value creation cycles, so that the extensive transport of products and resources can be avoided [4]. In addition, the spatial agglomeration of producers and customers simplifies the return of used products to regional material cycles [5]. Furthermore, local on-demand production reduces overproduction and storage costs for semi-finished and finished products [6]. **Social sustainability** is promoted by involving a large variety of regional actors to secure and create local jobs and increase the quality of life on-site. Furthermore, the local value chains facilitate equivalent working standards. Local production moreover promotes regional structures for value creation (investments in local infrastructure, local qualification of skilled workers), which promotes **economic sustainability**. In addition, the spatial proximity between producer and customer simplifies the fulfilment of region-specific requirements and the forecasting of changes in consumer behaviour [7].

II. Motivation

Many examples from different sectors of the economy partially fulfil the stated dimensions of local production (e.g. regional clusters bundle the competencies and resources of local producers, but the products are made for a global market). Patterns of local value creation, which are characterized by **(1) on-site production** with the **(2) involvement of local stakeholders and regional raw materials and materials** to **(3) meet regional needs**, only represent a small portion of value creation in the manufacturing sector. Since the three dimensions of local manufacturing (LM³) are often not met at the same time, the full potential of local production cannot unfold.

The research project "Digital Urban Production" funded by dtec.bw (Digitalization and Technology Research Center of the Bundeswehr) starts here and contributes to the targeted promotion of local value creation patterns. For this purpose, the project expands the understanding of the systematics of local value creation and develops principles for the design of local value creation systems and the development of corresponding business models. But not only the understanding, also the actual implementation is part of the project, i.e., the research results will be applied to a business model that is to be tested in the real-world.

The results of the study analysing the systematics of local production are presented in section III. The main influencing factors of local production are listed and assigned to the social subsystems that significantly influence them. Subsequently a concept for a local manufacturing network is presented for the sustainable production of customizable furniture in the Hamburg area (refer to section IV). Finally, concrete measures for designing the local production network are presented, which address the dimensions and key factors of local production (refer to section V).

III. Study On The Systematics Of Local Production

There are many scientific approaches that deal with the systematics of local production, but focus on different aspects (refer to Table 1).

Table 1: Differentiation of the research focus of different scientific approaches to the topic of local production.

Scientific approach	***Research focus***
Re-Distributed Manufacturing	regional circular economy
Urban Manufacturing	production in the city
Distributed Manufacturing	decentralized value creation

The variety of perspectives supports a comprehensive understanding of the research object. Due to the focus of the research, there is a risk that the relevance of influencing factors on local production will be over- or underestimated depending on the considered concept. As part of the dtec.bw project "Digital Urban Production" a study was performed, which aims to expand the general understanding of the systematics of local value creation combining the different research foci of the concepts mentioned.

For this purpose, the key factors and their relevance to the emergence of local value creation patterns were identified using an adapted sensitivity analysis according to Vester [8].

The analysis is based on a meta-review of publications on the different concepts. Knowing these key factors supports a targeted design and promotion of local value creation patterns.

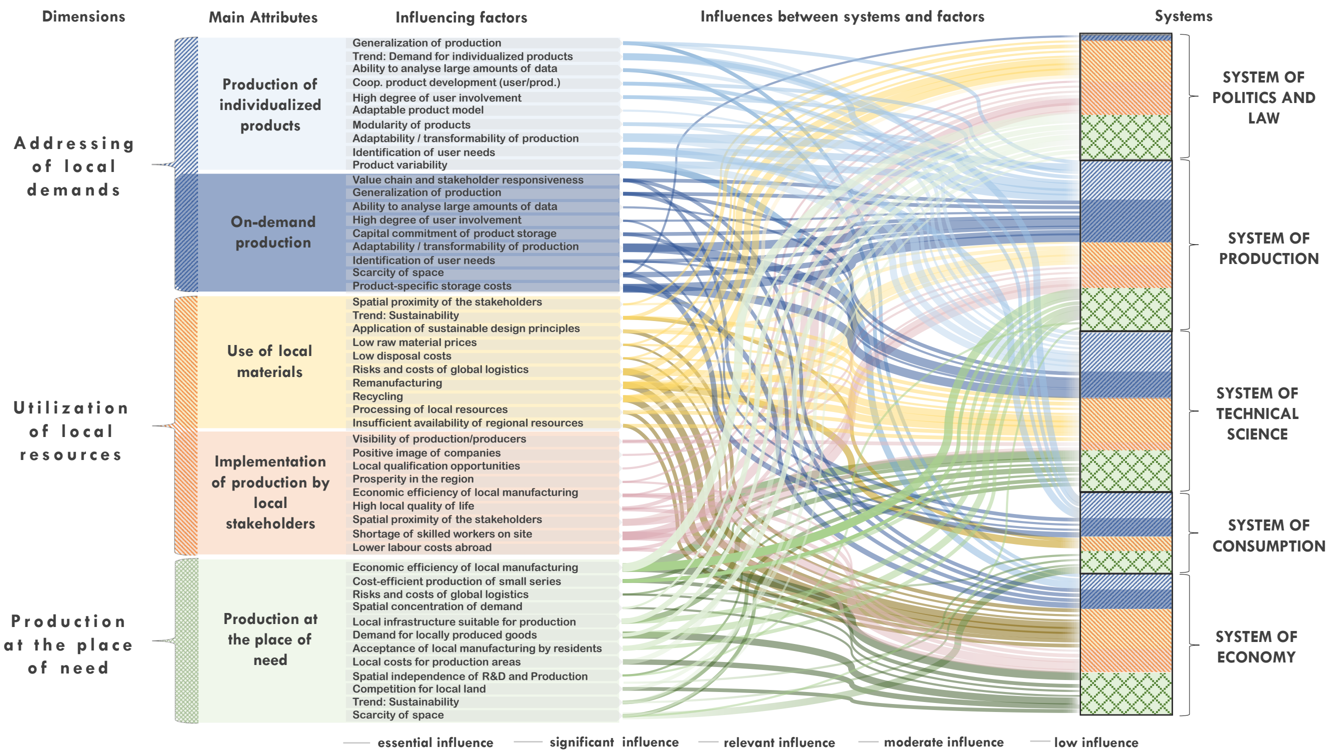


Figure 1: Assignment of the key factors of local production to the spheres of influence of societal sub-systems.

In a second step of the study an analysis was carried out to assign the identified key factors to areas of influence of different social sub-systems (e.g. politics and law, economy, production, consumption, technical science). This shows how the areas of law and politics, business, production, science and consumption support or limit the emergence of local production.

FIGURE 1 shows the identified influencing factors, their assignment to the dimensions of local production and the areas of influence of the social sub-systems. Future development of local value creation patterns is not just based on technological innovations from science or new business models in production. Rather the conditions for local production, which are largely determined by the areas of law and politics or the economic system, need to be adjusted (e.g. availability of skilled workers, local infrastructure).

IV. CONCEPT AND BUSINESS MODEL OF PRODUCTION NEXT DOOR

Knowing the dimensions and the associated influencing factors of local production enables the creation of a targeted design of value creation systems, which aim to produce at the place of demand, using local resources (actors and materials) to satisfy specific, regional needs.

The concept "Production Next Door" (ProNeD) was developed as part of the dtec.bw project "Digital Urban Production". ProNeD creates a **platform-based production**, which combines the potentials of global product development and manufacturing on-site. Besides this it provides the customer with easy access to **locally produced goods,** allows them to **individualize** them and ensures an **efficient coordination** between all participating stakeholders along the product development process.

The development of products is done by including global, open communities using the wisdom of the crowds [9]. These ideas are then provided with a free license (open source hardware), so that they can be manufactured wherever they are needed. This enables the establishment of regional value creation networks, which manufacture and distribute these products locally. The customer can buy them in a webshop and also adapt them to his/her individual requirements (customizing).

The different steps of the value creation process (development, manufacturing, sales) are digitized and supported by a virtual platform to integrate the activities of the different groups of actors (developers, producers, customers). The goal of digitization is to enable an efficient integration of production-ready designs through global communities, order-controlled, automated planning of dynamic, regional value chains and user-friendly product customization for the customer.

A. ProNeD's goals

The main objective of ProNeD is to establish a form of local, demand-driven production to promote ecologically, socially and economically sustainable value creation.

ProNeD enables on-site production for the customer for a product segment that was usually implemented by centralized, industrial production beyond the region. By reducing value creation cycles, transport routes are reduced and ***ecological sustainability*** is promoted. The spatial agglomeration of producers and customers also simplifies the return of used products to regional value creation cycles (e.g. repair, re-manufacture). The production is based on the principle of "on demand", and therefore helps to reduce overproduction as well as costs and emissions for storage of semi-finished and finished products. ProNeD contributes to ***social sustainability*** by involving a high diversity of regional actors to secure and create local jobs. ***Economic sustainability*** is achieved by promoting local value creation structures (investment in local infrastructure, local qualification of skilled workers). However, the costs of locally produced goods are often significantly higher than those of industrial production based on the division of labour (e.g. because of economies of scale). To counter this, ProNeD aims at a continuous digitalization of cross-company product manufacturing to improve costs compared to the currently common individual commissioning (e.g. by reducing initiation and coordination costs). Development costs are reduced through the implementation of global communities and the use of open product licenses, which enable the product to be manufactured in a variety of local value creation networks. Furthermore, the benefit of the service for the customer is extended by product individualization.

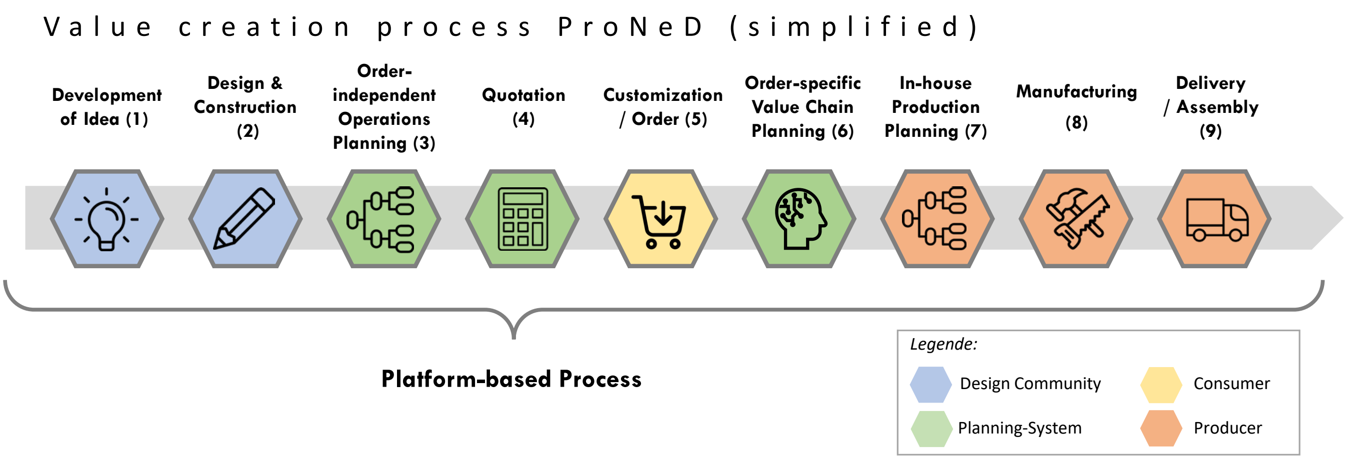


FIGURE 2: PRONED VALUE CREATION PROCESS.

B. *ProNeD's process*

ProNeD establishes a manufacturing platform that supports the product development process from the initial idea to the delivery of the product (see FIGURE 2). The platform therefore integrates the activities of global communities for development, the planning of local value chains and the customization by customers. With this ProNeD aims to reduce transaction costs between the large number of players involved as well as to align the product development with the capacities of local production on-site.

The process starts when a customer or developer publishes an idea on the platform (1). A community vote is used to select the most promising ideas fitting best to the concept of ProNeD (e.g. producibility in the local network, sustainability criteria, expected production costs, design). During the phase of design and construction (2), a team of developers converts the idea of the product into a digital product model, which can be produced directly by the local network. To support the developers with the construction of a finalized product model producers participate in the team for development. A product maintainer supervises the distributed development process. The platform guides the team through a standardized development process in virtual development spaces [10]. Based on the finished product model the technical system performs order-independent automated operations planning (3) to identify potential local value chains for manufacturing. In addition, the identified value chains are evaluated according to predefined criteria chosen by the customer (e.g., cost, time, environmental sustainability). The creation of the sales offer is automatically prepared by ProNeD's sales system (4) based on the product model and finalized by the product maintainer. Finally, the product is offered to the customer on the sales platform. The customers are able to adapt the product according their individual needs via customization (5). They can modify its visual and functional properties (e.g. dimensions, materials, colour) and influence the systemic design of the value chain (selection of criteria for determining the producers) according to sustainability criteria (e.g. use of green electricity by the production companies, preference for companies with high social commitment). The purchase of the customer causes the next step: order-specific value chain planning (6). Depending on the wishes of the customer and currently available resources in the production network, the planning system selects the most suitable value chain for manufacturing of the product and awards a contract to the producers involved. The planning system supports the control of the cross-company manufacturing process (7) by continuously communicating the current product status to the stakeholders involved. Once manufacturing is completed, the distribution system manages the interaction between the producers and the customer to coordinate the delivery and assembly (8).

C. *Stakeholders and dimensions*

Value creation at ProNeD is determined by three groups of stakeholders: Developers, producers, customers.

Developers operate within global, open communities. Depending on their skills and preferences, they take on the role of idea providers, designers and design engineers. Through their participation at ProNeD, developers can implement and commercialize their own product ideas with the support of a community and production network. Depending on their role and contribution during the development process, developers receive pro-rata compensation for each product sold through the platform to which they have contributed.

The **producers** are regional crafts businesses or small manufacturers. They have different professions and specializations. By combining the diversity of regional manufacturing capacities, it is possible to realize a wide range of potential products. On the one hand, the regional producers expand their business field by being part of the ProNeD network and gain access to new customer segments (see Stoltenberg et al. in this volume). Furthermore, the producers reduce uncertainty (fluctuating prices, risk of not being awarded a contract in the initiation phase) and the effort required to initiate a contract.

The **customers** are local individuals who value regional or individual product manufacturing. By specifying personal preferences, the customers can shape the value chain and learn in detail how their products are made (transparency regarding the value chain). In addition to the social-ecological benefits, customers using ProNeD benefit from opportunities to individualize the product, an efficient initiation and ordering process and the selection of criteria which are considered in the supply chain deployment (economic-functional benefit).

D. *Viability of the concept ProNeD*

The development and operation of the ProNeD platform must be ensured to receive a viable business model. For this purpose, a pro-rata commission to the platform for each product sold will be implemented. However, each local value network serves only one regional market, which limits the target group in terms of space. Funding of the platform is also secured by the fact that the concept can be transferred to other regions or cities. In the pilot phase, the project will be realized in Hamburg focusing on furniture production.

V. DESIGN OF THE PRONED MANUFACTURING PLATFORM

The results of the study about the systematics of Local Manufacturing presented in section III show the need for different social sub-systems to work together to promote local forms of value creation. Over the course of the project "Digital Urban Production", we contribute to the promotion of Local Manufacturing mainly through the system of science and the system of production.

In the system science we perform research and development activities which focus on combining global product development with Local Manufacturing activities to improve the flexibility and agility of local value chains. Furthermore, we act in the sphere of the system production by developing a new value creation concept ("Production Next Door") for regional furniture production. Within both systems we address and therefore *directly* influence various factors of local production (e.g. adaptability/transformability of production, cooperative product development). However, we *cannot directly* influence the characteristics of many factors that affect the sphere of the systems politics and law, economy or consumption. To those we can only *react* by choosing the context and the design of the business model.

TABLE 2, TABLE 3 and TABLE 4 list measures, which were developed as part of the project to promote the concept ProNeD within the Hamburg Metropolitan region and to establish new structures for local production. The lists also show which measures directly impact the characteristics of the key factors (active measures) and which merely react to the situational characteristics of key factors (passive measures).

With this we see that most of the active measures of the concept ProNeD affect key influencing factors of the dimension **"addressing of local demands"**. By contrast, the measures listed respond primarily to the characteristics of the influencing factors in the dimensions **"production at the place of need"** and **"utilization of local resources in value creation"** by selecting the appropriate context (product segment, branch, location) and designing the business model (e.g. demand for locally produced goods). These measures can be classified as passive.

TABLE 2: "PRODUCTION AT THE PLACE OF NEED" AND ITS INFLUENCING FACTORS OF LOCAL MANUFACTURING AND ASSOCIATED DESIGN MEASURES.

Production at the place of need	
Influencing factors of local production	***Associated design measures of the ProNeD concept***
Economic efficiency of local manufacturing	Selection of a market segment with a higher price level
Cost-efficient production of small series	Platform-based integration of development, planning and sales to reduce transaction costs along the value chain / Digitization of coordination processes in the local value network
Cost-efficient production of small series	AI-based decision systems to optimize value chain design and selection
Cost-efficient production of small series	Production-ready design by global communities to ensure efficient manufacturing by local producers
Cost-efficient production of small series	Provision of product portfolio through community-based product development to reduce development cost
Local infrastructure suitable for production	Selection of the Hamburg metropolitan region due to suitable infrastructure for the production and delivery of furniture for a regional market (e.g. energy security, availability of service providers in the field of IT or machine technology, logistics service providers)
Demand for locally produced goods	Selection of the Hamburg metropolitan region due to urban, and wealthier target group than the national average
Spatial independence of R&D and Production	Crowd-Engineering-Platform: using crowd engineering platform to involve global developer community in product development for the local production network
Trend: Sustainability	ProNeD's value proposition for the customer based on sustainability
Trend: Sustainability	Customer choice for individual value chain design according to sustainability criteria (social, environmental)

Type of impact: ■ passive ■ active

TABLE 3: "UTILIZATION OF LOCAL RESOURCES" AND ITS INFLUENCING FACTORS OF LOCAL MANUFACTURING AND ASSOCIATED DESIGN MEASURES.

Utilization of local resources	
Influencing factors of local production	***Associated design measures of the ProNeD concept***
Shortage of skilled workers on site	Selection of the Hamburg metropolitan region due to high availability of skilled workers and training options
Spatial proximity of the stakeholders	Selection of the Hamburg metropolitan region due to high availability and spatial proximity of craft businesses
Positive image of companies	Selection of the woodcrafting industry due to its positive reputation among the population
Positive image of companies	Selection of producers with regard to value-based management
Visibility of production/producers	High level of transparency to present the product manufacturing process and the producers involved to the customer
Application of sustainable design principles	Sustainability as a central criterion for the selection of products in the idea phase and the design of the products in the design phase on the crowd engineering platform

Type of impact: ■ passive ■ active

TABLE 4: "ADDRESSING OF LOCAL DEMANDS" AND ITS INFLUENCING FACTORS OF LOCAL MANUFACTURING AND ASSOCIATED DESIGN MEASURES.

Addressing of local demands	
Influencing factors of local production	***Associated design measures of the ProNeD concept***
Product-specific storage costs	On-Demand Production: Start of product manufacturing takes place only after the order is placed by the customer
Adaptability / transformability of production	High diversity of players in the regional value creation network
Adaptability / transformability of production	Participating Stakeholders are generalists
Adaptability / transformability of production	Highly flexible composition of local value chains through automated value chain planning
High degree of user involvement / Cooperative product development	Open access to product development for customers and developers
High degree of user involvement / Cooperative product development	Transparent presentation of the product development from the first idea to the delivery of the product via the ProNeD platform
Ability to analyze large amounts of data	Use of technical analysis systems to evaluate customer requirements and participation of producers in the value creation process

Type of impact: ■ passive ■ active

As an actor operating in the production and science system, we can thus serve the dimension "**addressing of local demands**" well. However, for Local Manufacturing in the sense of LM³ to work, the other dimensions of local production must also be addressed. For this, however, it is necessary to operate in the other sub-systems. Further efforts to promote local production must therefore increasingly address the scope of the systems politics and law, economy and consumption.

VI. Conclusion

As global value creation, based on the division of labour, often causes various ecological, social and economic challenges, local production has the chance to counteract these negative effects. Thus, it has the potential to establish a more viable form of production, as it promotes ecological, social and economic sustainability.

For this potential to be realized, the three dimensions of local production must be considered (production at the place of need, utilization of local resources, addressing of local demands). The concept of ProNeD aims to address these three dimensions within its business model, that is based on establishing a platform-controlled value creation process for furniture production in Hamburg. The integration of a supraregional or global community for product development supports the creation of new designs, opportunity to participate in a value creation process for various actors as well as cost advantages. Since the platform controls the operations, coordination costs can be reduced. Manufacturing by local players enables individualization potentials that reach beyond those of industrial production. The involvement of the crafts can better serve the individual needs of consumers, which leads to more tailored products. These, in turn, give rise to hopes of a longer product life. ProNeD therefore promotes environmental sustainability by relying on local production on-site and thus not requiring long supply chains. Due to the manufacturing by local producers it also promotes social sustainability by supporting those, thus securing jobs and skills in the region. With ProNeD, customers can customize their products according to their needs and also influence the configuration of the value chain.

ProNeD can thus serve the three dimensions of local production and also the three dimensions of sustainability. However, as ProNeD is a concept of the project “Digital Urban Production”, it acts as part of the system production and science. In other parts, it has to adapt to existing circumstances and conditions. In order to ensure the success of this form of local production, efforts in those other parts of the society are necessary (e.g. promotion of the local infrastructure, training opportunities, etc.).

If all sub-sectors create the conditions for local production (in the sense of LM ³), each within its own framework, and thus ultimately work together, the way to more sustainable, stable value creation can succeed.

Acknowledgement

This paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project Digital Urban Production].

References

[1] J. S. Srai et al., “Distributed manufacturing: Scope, challenges and opportunities,” *International Journal of Production Research*, vol. 54, no. 23, pp. 6917–6935, 2016, doi: 10.1080/00207543.2016.1192302.

[2] P. Krenz, L. Stoltenberg, J. Markert, D. Saubke, and T. Redlich, “The Phenomenon of Local Manufacturing: An Attempt at a Differentiation of Distributed, Re-distributed and Urban Manufacturing,” in *Springer eBook Collection, Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems: Proceedings of the 8th Changeable, Agile, Reconfigurable and Virtual Production Conference (CARV2021) and the 10th World Mass Customization & Personalization Conference (MCPC2021)*, Aalborg, Denmark, October/November 2021, A.-L. Andersen et al., Eds., 1st ed., Cham: Springer International Publishing; Imprint Springer, 2022, pp. 1014–1022.

[3] P. Krenz, D. Saubke, L. Stoltenberg, J. Markert, and T. Redlich, *Towards Smaller Value Creation Cycles: Key Factors and their Interdependencies for Local Manufacturing*: Hannover : publish-Ing, 2022.

[4] A. S. Lowe, “Distributed Manufacturing: Make Things Where You Need Them,” in *Management for Professionals, Co-creation: Reshaping business and society in the era of bottom-up Economics*, T. Redlich, J. P. Wulfsberg, and M. Moritz, Eds., Cham, Switzerland: Springer, 2019, pp. 37–50.

[5] C. Turner *et al.,* “Sustainable Production in a Circular Economy: A Business Model for Re-Distributed Manufacturing,” *Sustainability*, vol. 11, no. 16, 2019, doi: 10.3390/su11164291.

[6] A. Petrulaityte, F. Ceschin, E. Pei, and D. Harrison, “Supporting Sustainable Product-Service System Implementation through Distributed Manufacturing,” *Procedia CIRP*, vol. 64, pp. 375–380, 2017, doi: 10.1016/j.procir.2017.03.070.

[7] D. T. Matt, E. Rauch, and P. Dallasega, “Trends towards Distributed Manufacturing Systems and Modern Forms for their Design,” *Procedia CIRP*, vol. 33, pp. 185–190, 2015, doi: 10.1016/j.procir.2015.06.034.

[8] F. Vester, *Ausfahrt Zukunft Supplement: Material zur Systemuntersuchung*. München.

[9] P. Krenz, J. P. Wulfsberg, and F.-L. Bruhns, “Unfold Collective Intelligence!: Erschließung neuer Wertschöpfungspotenziale durch Entfaltung kollektiver Intelligenz,” in *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, pp. 152–157.

[10] P. Krenz, J. P. Wulfsberg, and F.-L. Bruhns, “Granulares Wissensmanagement - Schaffung einer virtuell gestützten Realität durch funktionale Arbeitsräume,” in *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, pp. 409–415.

Acceptance of Local Production among Regional Stakeholders. Results of Qualitative and Quantitative Research of Producers and Consumers

Lisa Stoltenberg*, Pascal Krenz, Julia Markert, Dominik Saubke
Helmut-Schmidt-University
Hamburg, Germany
*info@productionnextdoor.com

Abstract – **Against the background of global warming as well as (impending) economic crises, local production models are becoming increasingly important. This is the starting point for the dtec.bw-funded project „Digital, Urban Production" with its concept "Production Next Door", which aims to establish a regional, digitally linked production network in the field of furniture manufacturing in Hamburg. The project is based on the idea of having customizable furniture manufactured by regional producers, thereby promoting the regional economy and circular economy initiatives. While the benefits of local production are already much discussed and known at the political and scientific level, it is questionable how they are perceived by regional actors, on whom the success of local production crucially depends. In order to explore to what extent regional actors accept local production, interviews with producers and a survey with consumers were conducted. This article presents the results of the interviews conducted so far and elaborates conditions necessary for the acceptance of local production. Barriers as well as conflicts of interest are also revealed and it is shown how ProNeD, as a concept for local production, plans to face them.**

Keywords - Local Production, Urban Production, Regional Stakeholders, Sustainable Production, digital business models

I. Introduction

Both the Covid-19 pandemic and the war in Ukraine are a reminder of how dependent the economies of individual countries have become on global events. For some time now, however, there have been efforts to pay more attention to the regional economy again.

The aim is not only to reduce dependence on global developments which - by their very nature - are difficult to control, but also to support the resilience of the economy [1] and to promote (often) smaller, regional players and value creation structures [2]. Another key contribution is to reduce value cycles in order to strengthen the environmental sustainability of product manufacturing (e.g., by reducing transport distances) [3].

As part of the dtec.bw project "Digital, Urban Production", the concept "Production Next Door" was developed, which aims to promote a local value creation process in the field of furniture manufacturing in Hamburg and thus to strengthen the regional economy.

With this approach three sustainability dimensions are addressed:

- the ecological sustainability (by shortening supply chains)
- the social sustainability (by supporting the regional manufacturers and value creation structures)
- the economic sustainability (refer to Krenz et al. in this volume)

II. Production Next Door

"Production Next Door" (ProNeD) refers to a new form of local production through regional, digitally connected value creation. The main objective is to strengthen the regional stakeholders and to contribute to social and ecological sustainability.

At the same time, the aim is to develop products globally in order to obtain innovative product design ideas and to give all interested parties the opportunity to contribute. The resulting designs are provided under a free license (open source hardware) and are thus available to the local value creation networks for marketing and manufacturing. The finished products are then offered in a webshop, where customers can select and personalize them according to their preferences. Once the order has been placed, the appropriate local producers will be contacted in order to manufacture the chosen product. These producers are typically small craft businesses (e.g. carpenters). Delivery and assembly are done by the businesses themselves. The value chain, from development and production to sales, is digitized end-to-end to ensure cost-efficient coordination between the stakeholders.

Since ProNeD involves supra-regional communities for product development, the value creation process for the producers changes (refer to Figure 1). Usually producers perform all the production steps themselves – they develop the products (in constant coordination with the customer) and handle the supply chain planning. Within the context of ProNeD, this step is performed by supra-regional communities. The customer adds his ideas via the customization options when purchasing in the web store and the technical system handles the involved cross-company planning processes.

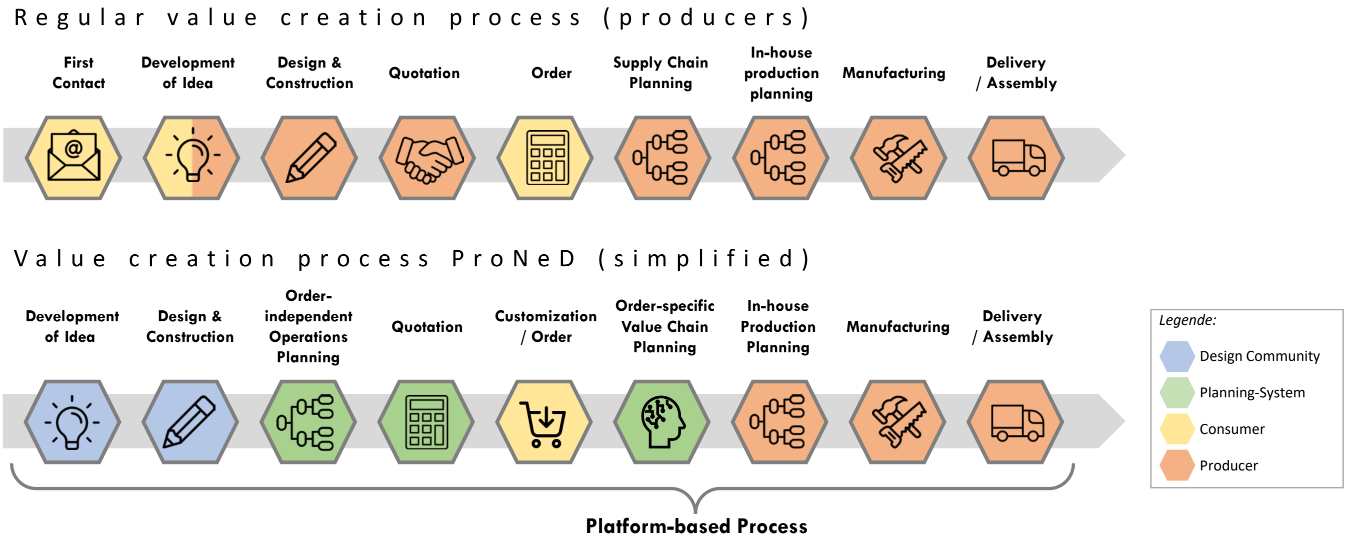


FIGURE 1: COMPARISON OF THE PROCESS MODELS.

In the case of carpenters, their usual value creation process begins with initiating contact, often includes a visit to the customer's home and the creation of sketches. Quotation preparation and design can go through several coordination loops with the customer. Then the manufacturing follows. Finally, the producer delivers the product and assembles it, if necessary.

In sum, ProNeD will shorten the producers' usual value creation process by relieving the carpenters of the initiation phase (see FIGURE 1). This gives the producers more time again for their core task - manufacturing.

III. AIM OF RESEARCH

Local Manufacturing aims to contribute to ecological sustainability by focusing on small production cycles. It also promotes the strengthening of regional actors, thus contributing to social sustainability and supporting regional resilience. Besides this, also economic sustainability is addressed by involving supra-regional communities in product development and optimizing value chains through an AI-based system. However, it is questionable to what extent the mentioned value creation process of ProNeD is of interest to the regional actors.

In the case of ProNeD, the focus is primarily on small craft businesses. However, their order situation is currently very good. They have a shortage of staff rather than a shortage of orders. This is why the following questions arise:

- Why should/would producers want to be part of a local production network (e.g. ProNeD) even though their business is doing well?
- What would other concepts and business models of local production (e.g. ProNeD) have to offer them in order for them to participate?
- What could potentially stop them from participating?

On the demand side, most customers usually buy furniture from industrial production. In the well-known stores they have a wide variety and can buy furniture at moderate prices.

Although sustainable and regional consumption in case of groceries (as a typical *consumer* good) is becoming increasingly important to consumers, it is not clear, if this trend also applies to products that are not *consumed* daily but *used*, like furniture.

This leads to the following questions:

- Are customers even interested in buying furniture locally?
- And under what circumstances would they be willing to do so?
- What is preventing them to buy locally produced furniture?

To answer precisely these questions, we interviewed the main actors of a local production - producers, more specifically carpenters, and consumers. The answers we found are helpful both for the establishment of local production in general and for the elaboration of ProNeD's business model.

IV. METHOD

In order to find out if and under which conditions the producers are willing to participate in a regional manufacturing network we interviewed them first, since the concrete design of the local production network depends on their skills, equipment, availability and pricing habits. The consumers could therefore only be meaningfully interviewed after the findings from the producer interviews had been incorporated into the development and the configuration of the concept for local production.

A total of ten two-hour interviews were conducted with producers, six of whom are based in Hamburg, four in the surrounding area and all interviewees specialize in furniture construction. As the number of employees ranges from three to about 35, they can be classified as micro and small enterprises. The interviews took place at the respective carpentries and usually included a tour of their production facilities. With one exception, the interviews were conducted with the business managers.

The consumer survey was conducted digitally about six months after the interviews with the producers using an online panel from a market research company. 300 consumers living in Germany were surveyed. All of them had to have bought furniture in the last three years and had to be able to imagine buying furniture either from a carpenter or online in general. Another criterion was a monthly household net income of at least 3000 €. The online questionnaire contained 20 questions and took approximately ten minutes to complete.

V. Findings

Within the results of the interviews and the survey, we have identified four main topics that are important for the establishment of local production in general, as well as for the different actors. In the analysis process, conflicts of interest between the consumers and producers emerged that need to be resolved if local production is to be successful. In the following, these four main topics and conflicts of interest will be presented, as well as how ProNeD as a concept of local production intends to respond to them.

1) Pricing

As the producers perform a craft, they are in a different market segment than industrial furniture production. This is also accompanied by higher prices. In the interviews we found that competition among the carpenters themselves is also high. In some cases, they spend a lot of time initiating the ordering-process with the customer, only to be undercut by a competitor that the customer then chooses.

It is therefore not surprising that the carpenters have concerns that a local production network could lead to a price competition between the producers. The companies know they cannot compete with industry in terms of price and are concerned that they would have to lower their prices as a result of the network and would therefore no longer be able to cover their costs adequately.

Consumers usually buy industrially manufactured furniture – in our survey 76 % said they buy from big well-known furniture stores. Price is a decisive purchase criterion for them (for 87 of our respondents, it was very important or important). That is why for consumers the high prices of carpenters are a barrier to purchase (for 52 % it was a reason not to have bought from a carpenter so far). The willingness to pay for furniture increases only partly as net household income rises.

Therefore, pricing is a very sensitive topic for the producers as well as for the consumers and leads to the dilemma, that the prices of the products a local production (i.e. ProNeD) offers must address the expectations of the consumers on the one hand and on the other, secure that the participation in the network is financially worthwhile for the carpenters. Otherwise customers would continue to buy industrial products and producers would not participate in the network.

Local production must therefore offer additional benefits apart from price for which customers are willing to pay (more). In general, customers appreciate options of individualization and a regional origin of the products. The majority of our respondents (56 %) would be willing to pay between 6 % and 20 % more if the product was regional and designed according to individual wishes. But also, almost a fifth would spend nothing or up to 5 % more in this case, and only a third of respondents would spend between 20 % and 50 % more. So there need to be other aspects that motivate customers to buy locally produced furniture.

For this reason, a special purchasing experience would be a chance, as well as very distinctive products. In the survey, we found that consumers are willing to pay more if a piece of furniture fully meets their requirements and is very special. However, this is precisely one of the strengths of ProNeD: The outsourcing of the design process, that includes idea-contests, promises special pieces of furniture, which can be produced unproblematically due to the high skills and flexibility of carpenters and can still be adapted to the individual wishes of customers.

In addition, a price advantage can be realized by relieving the carpenters of the initiation activities, such as customer contact, measuring the customer's space, writing an offer etc., and thus costs. For the carpenters it also minimizes the risk of not being awarded a contract after already having invested time and potentially money for preparation.

Beside this, price competition between producers must be avoided by all means to ensure not jeopardizing the goal of strengthening the regional economy and promoting regional companies. This is to be achieved by working out a pricing system that is acceptable to all, in cooperation with the producers.

2) Level of individualization

The manufacturing of individualized products is the core business of all carpenters, which are focused on complex, highly individual furniture. Their market segment lies in personalized/unique production, with which they can distinguish themselves from industrial furniture production. Especially the manufacturing of these unique, very special products is also often a pleasure of their job and they appreciate facing new challenges in craftsmanship.

Although customers usually buy industrially manufactured products, developments such as mass customization show that the trend towards individual products is increasing and that today's technology allows more and more personalization, also in the mass market. It is therefore not surprising that for almost half of the respondents (47 %), the possibility of individualizing the products is the most interesting aspect of ProNeD. Thereby the majority of respondents is interested in being able to have an impact on the size (73 %), colours (67 %) and materials (65 %) of the product. Other options of personalization (shape, engravings, technical features) were not very interesting to the consumers. This fits with the fact, that too much effort in the ordering process is a reason to cancel a purchasing process or refrain from buying (e.g. at a carpenter).

In conclusion, a degree of individualization must be found that serves as a distinction from industrial furniture production (and also inspires the carpenters), but does not increase the costs of manufacturing or overwhelm the customers in terms of choice.

ProNeD can meet the requirements for individualization by offering more options for customization than the furniture industry, which often only offers two to three different sizes and two to three different colours.

In the context of ProNeD, the customers can specify three main attributes of the products:

- the sizes of their furniture pieces (in exact cm),
- choice of a variety of colours (exact number to be determined)
- choice of a variety of different materials (exact number to be determined).

In addition, customers can choose between different criteria that determine which producers are considered for production. These can be criteria of sustainability (such as that the producers are particularly socially committed or use green electricity) as well as criteria relating to delivery time or price. Both customization aspects thus strengthen the customer's attachment to his/her product.

Further options of individualization (e.g. changing the shape) are not included, because these would run the risk of overwhelming customers.

Producers benefit from the fact that the externalization of designs gives rise to new product ideas that provide them with new challenges. In addition, the producers themselves are free to participate in product development if they wish to do so.

3) Contact to customers

As shown above, the usual value creation process of a carpenter includes contact with the customer, especially in the initiation phase. During the interviews it became evident that the carpenters value this contact with the customer and also see consulting as an important and identity-forming part of their work. The carpenters themselves see their role as someone whose main tasks is to provide advice. They enjoy customer contact and do not want to miss it. In addition, customer contact often forms a basis of trust through which the customer base is secured. Securing their customer contact is important because not every inquiry that reaches the carpenters actually becomes an order. That is why some carpenters are sceptical about passing the initiation process to the platform.

The survey showed the regionality (as a part of sustainability) of ProNeD is a key factor of interest for the consumers. Besides this, they like the idea of knowing where their products come from and it also seems to give them a feeling of control. Some said they liked the opportunity of visiting the producers as well. Nevertheless, customers are reluctant to buy from a carpenter because they worry that it will take too much effort (in our research it was a reason for one quarter of those who have not bought from a carpenter yet). On the other hand, when buying furniture, customers also appreciate personal advice – 30 % of those we have asked in our survey.

Consequently, for the carpenters, customer contact has been a crucial part of their daily work. Customers (especially online-shoppers), on the other hand, like to be independent [4] and only wish for contact when they need advice (as illustrated by the example of curated shopping). It is enough for them to know that the carpenter would be within reach if necessary.

Maintaining customer contact between carpenter and customer is not an option at ProNeD. In the case of online purchasing, there is very high competitive pressure, it is imperative to avoid overwhelming the consumer. To this end, any potential for abandonment during the purchase process must be minimized. It is therefore important to make it clear to the carpenters that forgoing customer contact does not mean a loss for them. ProNeD is not meant to be a replacement for their regular business, but an additional offering. Also, the contact between the customer and the carpenter is maintained, because the latter continues to carry out the delivery and assembly. The presentation of the value creation process by ProNeD as well as the option to choose between criteria for the value chain (customization of value chain) create a connection between consumer and producer. ProNeD offers a potential to facilitate the accessibility to the carpenter's craft and meanwhile reduces what consumers perceive as inconvenient or complicated when buying from a carpenter.

4) Online-Purchsase

Producers usually receive inquiries and orders by mail or telephone. They do not have an actual online sales department. For carpenters, it is common that their customers are not able to see or touch the product before it is manufactured or delivered. They can usually only provide a sketch or examples of their work.

This very fact of not being able to see the product before buying it is what keeps many customers from buying furniture online (in our survey 56 % of those who have not yet bought furniture online indicated this). This may also be a reason for not buying from a carpenter. Although furniture is still mainly purchased offline, the online sales market for furniture is becoming increasingly important [5]. To see or touch a product is especially important for customers in the case of furniture, because these are usually expensive and long-term purchases which are also difficult to return [4]. Warranty and return policies in particular are often a barrier to customers buying online as our survey showed (20 %).

For online purchases, it is important to build trust due to the lack of opportunity to see and touch the products [6, 7]. For this purpose, consumers must receive meaningful information about the product so that they can imagine it as well as possible. As mentioned before, customers expect a purchase to be unproblematic and quick, which is a main reason for online shopping [7, 8]. Thus, in online shopping, it is common and easy to compare products [4, 5]. Moreover, consumers often buy online because they can save money. For this purpose, they often use price comparisons [5,8]. On the internet a larger selection can be found, so the competition is higher and thus creates more pressure (e.g., regarding a special offer, price, very professional appearance, etc.)

As an online-retailer, ProNeD faces the problem of customers not being able to touch the product or see it in real life before buying. To address this issue, ProNeD will provide its offers on the website with detailed and appealing information about the products, especially to compensate for the lack of haptics [9]. The information about the products include the exact sizes, all functionalities, as well as statements about the materials used and, if necessary, care instructions. Pictures or sketches will be presented in a professional layout, in order to generate an attractive and trustworthy appearance. A professional website, with self-explanatory usability based on e-commerce benchmarks, is another mandatory requirement for this (see e.g. [9]). Furthermore, offering material samples could be an option that makes it easier for consumers to buy furniture online. It would also be possible to set up a showroom in which examples of furniture are presented. Quality assurance and warranty rights can also be used to generate trust.

Furthermore, to generate the necessary trust in its products ProNeD aims to make the manufacturing process as transparent as possible. For each product, the story of its creation is told (including design process, actors involved, origin of materials, etc.). This also creates a shopping experience that the usual furniture retailers do not provide.

The differences between online and offline purchasing suggest that the typical customer of ProNeD will be different from the one that carpenters usually serve. This means that customers who otherwise have no contact with craftsmanship can be reintroduced without having to change their usual buying habits. This may open up a new target group (online-shopper) for the producers and thus also expand the level of awareness for their own business.

These conflicts are briefly summarized in TABLE 1.

TABLE 1: CONFLICTS OF INTEREST AND PRONED'S PROPOSED SOLUTIONS.

Conflict and Perspective		**Interest**	**Actions by ProNeD to solve the conflict**
Pricing	Producer	Absence of price competition	Development of a pricing mechanism in cooperation with the producers; relieving producers from development and initiation phase
	Consumer	Moderate prices	Additional benefit for customers (customization, regionality); reduction of development and initiation costs
Level of individualization	Producer	Manufacturing of individual products, new challenges in manufacturing	Product development with community generates new/innovative designs and therefore challenges for the producers
	Consumer	Getting individual products, but without having too much effort with them	More but not too many customization options (customization of product) than in regular retail; impact on value chain (customization of value chain)
Contact to customers	Producer	Solid customer relationship	Customer gets information about the producer who manufactured his/her product; producer gets contact to customer when delivering and assembling the product
	Consumer	Independent and uncomplicated way of purchasing	
Online-Purchase	Producer	Focus on core activity (manufacturing) and not on new distribution channels	Sales are achieved via the platform (web store), producers do not have to take care of distribution and can still reach new target groups
	Consumer	Valid impression of the product before buying	Professional website with meaningful images and information; transparency of value creation process creates trust

VI. CONCLUSION AND OUTLOOK

It is worth promoting local production because it can contribute to environmental and social sustainability. However, that does not automatically cause appreciation by local stakeholders on-site. This very acceptance is the subject of this paper and was evaluated using the example of the project "Production Next Door".

As we have demonstrated, local production generates some concerns among stakeholders that may hinder participation in local value creation. For the producers, competition on prices and the loss of customer-contact are such reasons. Barriers for consumers regarding local production are the high prices of the products as well as the time and effort of the ordering process.

However, the case of ProNeD shows, that local production also offers potential for regional actors. In the case of ProNeD, producers get the chance to reduce their initiative activities and costs and get the chance to manufacture extraordinary products or to enter a new target group by using another distribution channel. By efficiently integrating local competencies to serve the needs of customers (sustainability, individualization) and at the same time creating a special purchase experience and proximity to the producers, consumers' willingness to pay higher prices is ensured.

Consumers get products that they can customize to their preferences while meeting their desire for more regionality (whether due to wishes for control or sustainability efforts). In addition, they can have their products customized to a greater extent than in industrial retail. Also, the desire for better quality, which is often associated with durability, and good materials, is met through the manufacture by carpenters. At the same time, they get their products as easily as through usual online-shopping and therefore more easily compared to buying from a carpenter.

Nevertheless, the results showed that pricing is the most sensitive topic and is the factor on which the success of a local production strongly depends. Therefore, it is very critical to ensure that no competition in prices between the carpenters appears, especially since the goal of local production is to strengthen small and micro enterprises.

It is clear that ProNeD's service is not an alternative for everyone, because the prices will still be higher than those of the market leaders of the industrial furniture production. To achieve this, further approaches would need to be developed and implemented (e.g. cost-efficient small-scale production by local companies through modern manufacturing technologies, / digitalization of internal manufacturing processes). In addition, the framework conditions would have to change in order to promote local production (such as increasing costs for logistics or increasing requirements for constant environmental and labor standards along the value chain).

However, for those who appreciate supporting regional actors, working on the protection of the environment and innovative products, local production (e.g. in the form of ProNeD) is a suitable alternative. This applies to both consumers and producers.

ACKNOWLEDGEMENT

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project Digitale, urbane Produktion].

References

[1] A. S. Lowe, "Distributed Manufacturing: Make Things Where You Need Them," in Management for Professionals, Co-creation: Reshaping business and society in the era of bottom-up Economics, T. Redlich, J. P. Wulfsberg, and M. Moritz, Eds., Cham, Switzerland: Springer, pp. 37–50, (2019).

[2] D. T. Matt, E. Rauch, and P. Dallasega, "Trends towards Distributed Manufacturing Systems and Modern Forms for their Design," Procedia CIRP, vol. 33, pp. 185–190, (2015), doi: 10.1016/j.procir.2015.06.034.

[3] C. Turner et al., "Sustainable Production in a Circular Economy: A Business Model for Re-Distributed Manufacturing," Sustainability, vol. 11, no. 16, (2019), doi: 10.3390/su11164291.

[4] B. Engels, "Generation Onlineshopping: Eine empirische Analyse unter Jugendlichen," Köln: Institut der deutschen Wirtschaft (IW), IW-Report 22/2020, (2020).

[5] Statista: Deutschland: E-Commerce-Nutzer im Segment Möbel / Statista. https://de.statista.com/prognosen/491757/prognose-der-e-commerce-nutzer-moebel-und-haushaltswaren-in-deutschland (2022). Accessed 30 August 2022.

[6] Al-Debei, M.M., Akroush, M.N., Ashouri, M.I.: Consumer attitudes towards online shopping. Internet Research (2015).

[7] Ahrholdt, D., Greve, G., Hopf, G.: Erfolgszusammenhänge beim Online-Shop. in: Online-Marketing-Intelligence, Springer Gabler, Wiesbaden, pp. 305-346. (2019).

[8] Haas, H.: E-Commerce - Erfolgsfaktoren von Online-Shopping in den USA und in Deutschland, 1st edn. Deutsches Institut für Wirtschaftsforschung. Sonderhefte, v. 168. Dunker und Humboldt (2015).

[9] Deges, F.: Kaufprozess und Kaufverhalten im E-Commerce. In: Grundlagen des E-Commerce, Springer Gabler. Wiesbaden, pp. 71-84. (2020).

Community-based replication of Open Source Machine Tools

Luisa Lange*, Michel Langhammer**, Sonja Buxbaum-Conradi, Manuel Moritz, Mohammed Omer, Tobias Redlich, Jens P. Wulfsberg
Helmut-Schmidt-University
Hamburg, Germany
*luisa.lange@hsu-hh.de, **michel.langhammer@hsu-hh.de

***Abstract* – The number of developments of open-source hardware (OSH) has rapidly increased within the last years. One special form of OSH are machine tools, which are developed in an open-source manner, so called Open Source Machine Tools (OSMTs). OSMTs enable the manufacturing of hardware artefacts within open labs, fab labs and open production networks. Additionally, the distributed design and development as well as the replication process of OSMTs are aimed on increasing the technological literacy of its users within a community.**

The research presented in this paper focusses on the replication process of OSMTs within community-based workshops in the field of Fab City Hamburg. The current state of replication processes of already developed and prototyped OSMTs has been outlined based on interviews, observations and document analyses. First insights were gained whilst participating in community-based workshops as well as through conversations with the workshop participants and instructors along with OSMT designers and engineers. Subsequently the replication process of OSMTs was analysed and areas of improvement have been detected with regards to enhancing the technological literacy of the workshop participants. The authors conclude that OSH build workshops bare great potential of a new, holistic approach to achieving technological literacy within a short period of time.

With this paper, the authors identify important interconnections of OSMT replicability and technological literacy through replication workshops and form a basis for further research within this area.

Keywords – Technological Literacy, Open Source Machine Tools, Open-source Hardware, Build workshops

NOMENKLATUR

OSMT	Open Source Machine Tool
OSH	Open-source Hardware
OSS	Open-source Software
CAD	Computer Aided Design
BoM	Bill of Material

I. INTRODUCTION

The recent societal, environmental and economic challenges lead to a need of a rethinking our current value creation model. Open-source software and hardware are currently attracting more and more attention in politics [1], research and industry [2]–[4]. Open-Source Hardware (OSH) shows possible new ways of technical innovation, business models and development processes [5], [6]. Since the first patents of 3D printers have run out in the early 2000s, the development, modifications and replications of 3D printers has increased rapidly [7]. This development has influenced other OSH product categories, especially electronics (e.g. Arduino) medical devices [8]–[10], biology (e.g. open flexure microscope) and even the automotive industry (e.g. local motors).

One main difference between open-source software (OSS) and hardware is the replication of the collaboratively developed information and knowledge. In software, the user merely needs a computer system to replicate OSS code [11]. In open-source hardware there is a need of a physical infrastructure and an existing production system in terms of space, machines, material and organization of these components as wells as knowledge and skills to execute the replication processes. To minimize the threshold of replicating hardware by local communities, the demand for machines developed and documented in an open-source manner has increased within the last years [12].

Projects within the Hamburg community are focusing especially on the development of easy usable and replicable Open Source Machine Tools (OSMTs), which subsequently form the basis for starting an open lab anywhere in the world on a low budget and building up an open production landscape. The replication hereby is operated through educational workshops, so called build workshops, in which different types of OSMTs are replicated by different user groups. With the provision of assembly kits, consisting of pre-assembled parts and under the guidance of instructors and technical documentation, the components are assembled to a ready to use machine tool.

This new phenomenon of community-based replication processes offers a great chance to increase the scope of open-source hardware as well as increasing participants technological literacy. However, not much research has been performed in this field. Therefore, the replication workshops are studied and analyzed.

The researchers are analyzing the OSMT replication workshops in order to understand how OSH replication workshops should be designed to optimize their potential for OSH replicability and participants' technological literacy.

https://doi.org/10.24405/14533

II. Theoretical Background

The theory part of this paper aims to generate an overview on the context of open-source hardware, open-source hardware documentation, Open Source Machine Tools, open-source hardware replicability and technological literacy.

A. *Open-source Hardware*

The concept of *open production* comprises a comprehensive value creation framework, describing new forms of value creation in a bottom-up economy in which collaborative, distributed and self-organized processes throughout the entire value creation lifecycle are conducted from individual or organizational actors. The principle of openness, which describes the open interaction of sub-components within this system, is an essential element of the open production framework [13].

The principles of openness in terms of knowledge and information components is accessed in the development of open-source hardware which itself is a fragment of open-source [7], [13]. The open-source hardware association (OSHWA) defines open-source hardware as follows: "Open-source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design." [14]. Similar to open-source software in the 90s, open-source hardware is now being developed and refined throughout the whole world simultaneously, whilst the results are shared online with communities all over the world [7].

B. *Open-source Hardware Documentation*

In order to use the potential of OSH, technical documentation of the hardware is of elementary importance [15]. Therefore, a description of its documentation in form of a standardization has been outplayed in the DIN SPEC 3105 [16], [17]. This DIN specification describes a first community-based standard and certification of documentation content of OSH projects. The requirements for the documentation fully apply the rights of OSH, especially to modify, reuse and create hardware. The special feature of the DIN SPEC 3105 certification lies in its community-based assessment and its open-source license which allows modification and attestation by different communities [18]. The documentation of OSH mainly consists of its design files - primarily engineered with Computer Aided Design (CAD) tools and its Bill of Material (BoM) describing which material and components the hardware consists of. The OSH documentation is often shared in publicly accessible online repositories. An additional crucial part of the documentation, but not (yet) postulated by the DIN SPEC 3105, is an assembly guideline describing how the hardware is manufactured and assembled, to achieve the desired function of the design.

C. *Open source Machine Tools (OSMTs)*

In the last years, global production systems have been fundamentally reshaped. The increasing availability of electronics hardware such as microcontrollers, driver units, stepper motors, and sensors has accelerated the development of computer-controlled machines and digital fabrication [7]. However, currently only a minority of actors benefit from these machine tools, which are at the heart of this fast-paced development and are largely developed under closed source premises.

With the aim to increase the accessibility and availability of affordable and adoptable machine tools, Open Source Machine Tools (OSMT) have recently gained momentum [19]. Besides 3D printers, machines for laser cutting, grinding, milling, and metal forming have been developed according to open-source principles and contribute to widen the capability spectrum of the open production infrastructure. Through open design and collaborative development, modification, and adoption, the amount of OSMT designs continually increases [19].

D. *Community-based replication of OSH*

An open production system is characterized not only by openly available documentation of products and machines, but also by the replicability of designs. The factor of replicability is a significant difference from OSH to OSS. Unlike OSS, where only a PC-based environment is required to achieve replication of software code, OSH requires physical infrastructure such as material, energy as well as tools and skills [15]. A first analysis of the necessary factors for the replicability of OSH has been carried out by Antoniou et.al [20]. These factors describe an initially necessary provision of structural information, as well as requirements for the physical environment where the OSH artifacts are replicated.

These factors are summarized below:

- **Quality of documentation:** The quality of documentation increases with standardization of documentation (e.g. according to DIN SPEC), its accuracy, rigor and completeness as well as its dynamics which describes the collaboration and synchronization of documentation to current hardware design versions [20].
- **Completeness of documentation:** A complete documentation should also include a sufficient description of possible critical error events and troubleshooting measures. Additionally, there should be enough information stored to train a person to build the hardware version [20].
- **Accessibility to documentation, tools and material**: This point comprises the accessibility of OSH project documentation, also automated through metadata integration, the accessibility of the necessary materials and components as well as the required tools and equipment [20].
- **Ease of Manufacturing:** This factor determines what knowledge and skills are necessary, which materials and tools are necessary and which processes must be carried out for the assembly of the OSH design [20].

This set of factors is a first systemic approach to define dependency parameters of the replicability of OSH designs. Documentation factors as well as local physical requirements are mentioned.

E. *Technological Literacy*

Technological literacy is a term which has been defined in various ways [21]. One definition which is often used and that the authors find most suiting and comprehensive is the definition by Hansen (2003): "technological literacy is an individual's ability to adopt, adapt, invent, and evaluate technological solutions to positively affect his or her life, community, and environment [22].

Randall S. Davies has developed a framework for understanding technological literacy where he defined three successive levels of technology literacy:

1) Level 1: Awareness

Level 1 mainly focuses on the question *"What can this technology do?"* [21]. When reaching this level, learners are able to talk about the technology and understand what it does, however they are not yet able to use it [21].

2) Level 2: Praxis

At this level, the learners actually learn how to use the technology and will be able to complete simple tasks [21]. The lead question at this level is *"How do you use this technology?"* [21].

3) Level 3: Phronesis

The third level rather concerns the meta level and questions such as *"Why do I use or* not *use technology in this specific situation?"* [21]. It's mainly about the appropriate or inappropriate use of the technology, also depending on the context and situation.

These levels describe different stages of technological literacy and according to Davies those levels are sequential and require an "authentic context" in order to reach each of them [21].

In general, community-based OSH and OSMT replication workshops can be seen as a great potential to learn about hardware design, functionality, assembly and maintenance and repair possibilities. This project is focused on the research of how these replication workshops can be improved to fulfil this potential.

III. Project Description and Methodology

To put the research in context, the following section provides an in-depth project description as well as a detailed presentation of the planned methodology and research methods.

A. Concept and Research Design

The research regarding the OSMT build workshops takes place within the Fab City Hamburg. Fab City is a concept that originated in Barcelona and combines a network of cities with the common goal to produce nearly all goods the city consumes itself, by 2054 [23]. This thought is pushed forward by the help of strong local communities within the participating cities, which are connected globally. This concept of local production but global knowledge sharing is based on the already successful and influential open-source software movement [23].

The Fab City Hamburg is one of the first German cities to join this global network in 2019. This joining set the starting point of a community building process in which various actors like SMEs, non-profit organizations, fab labs, universities and individual persons and communities have been engaged to participate and form the legal entity "Fab City Hamburg e.V.". One output of this community is the execution of various workshops in the field of innovation consultancy and building OSMTs and other OSH prototypes. The conducted OSMT build workshops build the data foundation for this paper.

B. Methodology

Since research within this field is still at the very beginning, a qualitative and explorative research approach is chosen and presented in this paper [24].

This research is based on data collection through semi-structured expert interviews, observations and document analysis of OSMT documentation.

In a first step, interviews with trainers and workshop conductors had been carried out. These interviews were designed to gain a first understanding on the actual procedure of the workshops as well as possible pitfalls and problems that occur during the workshop. Subsequently, the build workshops were being observed. A special focus was set on the participants' questions that came up during the workshop, as well as other issues hindering to the process flow.

Furthermore, the participants of the workshops were asked for feedback, after the workshops had been conducted. Through this feedback process, the researchers enabled an anonymous comment on the events. This was important to create a space for also negative and constructive feedback as well as an understanding of the actual benefit of the workshops.

Additionally, a document analysis was carried out. This analysis mainly focussed on the build guidelines and design documentation which are stored in publicly accessible repositories. The documents were analysed and compared to the actual outcomes of the observations and the interviews.

An overview on the gathered data is shown in TABLE I.

TABLE I: OVERVIEW ON DATA.

Interviews	***Observations***	***Document analysis***
4 OSMT workshop instructors	3 3-D printer build workshops	Open source 3-D printer repository
3 OSMT developers	2 Laser cutter build workshops	Open source laser cutter repository

Through this method triangulation the internal and external validity of this research project is strengthened.

IV. Analysis and Results

After gathering the data, it was analysed, with regards to a standard workshop setup. Additionally, a focus was set on the intersections between the build workshop and acquiring technological literacy.

A. Build Workshop Phases

At present, workshops are carried out for an OSH laser cutter as well as an OSH 3D printer. The build workshops usually take two to four days, depending on the OSMT built as well as on the technical knowledge background of the participants. Each workshop is accompanied of minimum one instructor, depending on the number of participants as well as community mentors who have a broader understanding of the OSMTs design.

A first analysis has led to a preliminary outline of the recent build process. For a standard build workshop, six sequential phases have been observed, as shown in FIGURE 1.

1) Phase 1: Introduction

Phase 1 of the OSMT build workshops is aimed at creating a welcoming atmosphere as well as giving the participants a short introduction to the fields of open-source and OSMTs. During the interviews with the workshop conductors this phase was often emphasised: "They need the theory before this [the workshop]. A theory introduction into what are the parts that need to be considered or how that machine exactly works".

This phase sets the theoretical basis for the following workshop. By understanding these concepts, participants are also sensitised for possible minor errors that can happen during the process. Additionally, the participants are encouraged to be part of the open-source movement by coming up with improvement ideas during the actual build phase.

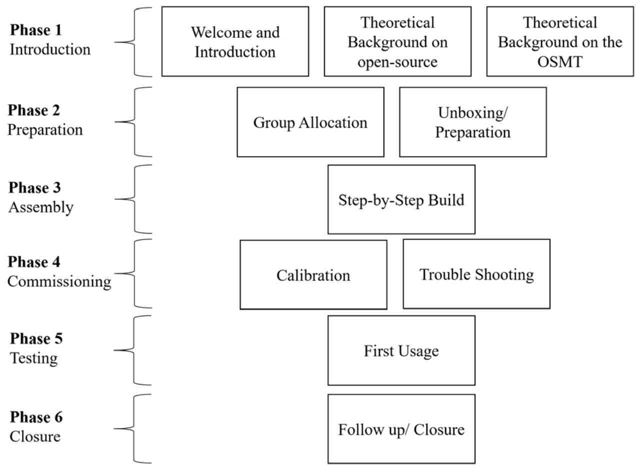


FIGURE 1: BUILD WORKSHOP PHASES.

2) Phase 2: Preparation

Phase 2 comprises the preparation of the actual building process as well as a suitable group allocation. Setting up all the required components and checking the BoM is not only essential for the later success of the build process. It also helps the participants to gain an overview on the actual parts and possible complexity of the OSMT they are building. During this phase, the participants often express their excitement about the whole workshop and the task that lies ahead.

For the group allocation, instructors should ensure, that a comfortable setting with mixed levels of expertise is reached for each group. In general, speaking from instructors' experience, the groups should not be larger than 3-4 participants for a 3D printer and up to 6 participants for a laser cutter build workshop.

3) Phase 3: Assembly

Phase 3 is the actual build process. This phase takes up the majority of time during the OSMT build workshops. During this phase, the participants are exposed to the whole assembly process in a step-by-step guidance from the mechanical frame assembly all the way to electronics wiring, sometimes even including soldering and installing high voltage components, such as a laser head. This phase is the core of the build process and takes up by far the most time. Hereby it is important that the participants can count on the support of a qualified instructor, as well as a conclusive build manual. Depending on the pre knowledge of the participants, the level of required support from the instructor can vary. One instructor described it as follows: "They're amateurs and they build it, so sometimes the result is not as good as expected. And then they're a bit frustrated. But then that's why we [the instructors] come in". This phase is also the phase which is most interesting from a research perspective in terms of learning experience, replication process and group dynamics.

4) Phase 4: Commissioning

After the assembly is completed, the OSMTs are mechanically calibrated. Especially with the laser component, this process is very challenging. In order to reach safety and quality requirements, the process has to be repeated several times. With a finished mechanical and electrical assembly, the software configuration takes place. The software parameter settings are dependent on the performed mechanical assembly and calibration and can therefore not be fully preconfigured.

Additionally, the trouble shooting process is included in this phase. The commissioning phase is the phase, where the instructors and mentors are supporting the most with their experience and knowledge. However, during this phase the participants already learn a lot about the machine's functionality and purpose as well as possible options for later maintenance and trouble shooting. After calibration, the machine tool is tested and occurring errors within the hardware and firmware are being addressed and fixed.

5) Phase 5: Testing

When calibration and troubleshooting are completed, participants can use their machines for the first time. Often this is perceived as the highlight of the workshop. Manufacturing something on a machine that itself has just been built is an important step to understanding the OSH replication concept. Unfortunately, time often runs out towards the end of a workshop, so that this part of the process needs to be considered with a time buffer to achieve the best learning experience.

6) Phase 6: Closure

Providing a proper closure and end to the workshop is important. By summing up the learnings and the pros and cons of each workshop, the participants are encouraged to reflect their individual learnings. It is often in this phase, that participants actually start realizing how much experience they have gained during the workshops and how much they actually have learned.

7) Follow up

After the workshops, a follow up is suggested. Reaching out to the participants a few weeks after the workshop is helpful to understand their personal perspective on the workshop. A follow up helps gathering possible improvement ideas as well as learnings the participants took away from the building process.

B. Additional Factors

Some additional, more general factors influencing the workshop flow and learning results of the participants could be observed during the analysis: workshop preparation, self-organized forming of sub-groups, the detail level of background information, quality check points and instructors' competency.

1) Workshop preparation

One vital aspect, for a successful workshop flow, is a thorough workshop preparation with regards to manufacturing and pre-assembling of sub-components, location and time planning. Especially when parts of the sub-manufacturing and sub-assembly are being outsourced to external companies or organizations who are not familiar with the OSMT design, a thorough quality check prior to the workshop is required.

An inadequate preparation can disrupt the flow of the workshop and discourage participants from an early stage on.

2) Self-organized sub-groups

During the workshops, it could be observed, that small sub-groups had formed within the allocated workshop groups. Especially in those groups with four or more participants, sub-groups had formed with regards to their prior knowledge and skills. This formation of sub-groups has also had an impact on the process flow as such. Whilst the groups were able to work faster by parallelising some of the process steps, the final outcome was more error prone.

Whilst teams that had not divided into sub-groups were communicating together "Could you please check what step has to be done next?", the teams which had formed sub groups were mostly unaware of the overall project status: "I don't know what we need this for, but I'll get started on it anyways"

By working "side-by-side" the internal group communication had changed and participants were not aware of what the other sub-group was doing. Hence, the final assembly was not always functioning as originally anticipated and re-work had to be done.

3) Background Information

One aspect that arose during all the workshops was the importance of detailed assembly guideline information. The participants often asked for further background information on the assembled components functionality and purpose. Questions such as "what does this component do?" were quite common. Therefore, the importance of interlinking technical background information of sub-components within the assembly guideline became apparent. During the interviews a workshop conductor and machine developer highlightened the importance of easy-to-understand guidelines as follows: "If you want actually people to repeat what you did, you should not think that the users are you. You should consider that the users are not knowledgeable at all and consider beginners."

4) Quality check points

In general, "quality check points" during the workshops are suggested, to detect errors, that cannot be corrected later, at an early stage. One example occurred during one of the 3D-printer build workshops. The printer bed had been installed in the wrong orientation. This error was discovered too late and the participants had to deconstruct major parts of the printer and restart again. Of course, this was not only time critical but also had a huge impact on the participants' motivation. Such occurrences could be prevented through intermediate "quality check points". Additionally, critical phases (such as the mentioned installation of the printer bed) should be specially marked in the assembly guideline documentation.

5) Instructor competency and effect on workshop flow

Especially in the parts of the replication workshops with higher technical complexity, the presence of a skilled instructor was essential for the flow of the workshop and the quality outcome of the assembled machine. Whenever the instructors were present, the dynamic within the group had also changed. Participants rather relied on the comments of the instructor and were not reflecting by themselves. This also led to an increased need of help in the later steps of the assembly since some of the basic information had not been perceived by the group. It was also interesting to see how the groups' sense of self-affirmation changed with the increased help of the instructors. If the instructor was offering a lot of support, the groups would also tend to ask more questions later on, rather than thinking for themselves first. This is an important aspect to keep in mind, when it comes to a further analysis of the individual learning journeys during these workshops.

During the later phases of the workshop, including the trouble shooting and the calibration, the experience of the instructors is especially needed. The part of the software configuration is the trickiest and requires more knowledge and skills to understand the software and to properly configure the respective parameters. Therefore, it is of advantage to use pre-tested software units, which can be transferred in a standardized way. If wanted and needed, the software configuration can also be "taught" separately. During the trouble shooting, very specific and detailed understanding of the replicated hardware is needed, which the participants often do not yet have. To improve the workshop flow, especially during this phase, the "accuracy, rigor and completeness" of documentation mentioned by Antoniou et.al [20] are crucial.

C. Intersections to technological literacy

When describing the six phases of a build workshop, it appears obvious to try to connect these six phases of the workshop to each of the levels of technology literacy. However, it quickly becomes apparent that it is not that simple. Whilst Davies [21] as well as Hansen [22] see technological literacy rather as a skill which should be acquired in a specific order, the build workshops pursue a more holistic approach.

When looking at the participants at the end of the workshops it can well be said that they have reached all three levels of technological literacy, the *Awareness*, the *Praxis,* as well as the *Phronesis*.

However, the holistic learning approach of the build workshops does not specifically distinguish between the single levels, technological literacy is rather reached as a whole. Even though *Phase 1 – Introduction* and *Phase 2 Preparation* largely take place at the *Awareness* level, they also already contain important aspects of the *Praxis* and *Phronesis* level. And whilst the main *Praxis* part takes place in *Phase 5 – Testing*, the participants already gain a lot of understanding on the use and functionality of the machine during *Phase 3 – Assembly* and *Phase 4 – Commissioning*.

By the end of all the build workshops, participants were not only able to understand what e.g., a 3D printer does and how it can be used, they also grasped the meaning of open-source, open production, collaborative replication and the general concepts of the technology's capabilities. One of the workshop instructors described this learning journey as follows: "… the first day they had some trouble and so on. And by the end of the last day, they were already solving all the problems that were happening with the machine."– This totally reflects the third level of *Phronesis* and the accompanying understanding of "effective use of technologies capabilities" [21].

V. Discussion and Conclusion

The six phases of the build workshop that have been outlined in this paper form a basis for further research within the field of OSH documentation and replication. Based on the knowledge gained from this project, future build workshops can be adjusted and optimized to evaluate the potential of OSH replication workshops. The authors suggest a more in-depth analysis of the single phases in future workshops. Especially the build and commissioning phase offer a lot of potential for future analysis.

The six phases have been based on the replication of OSMT. In the further course of this project, this framework will be further investigated during additional OSH build workshops. These should not only comprise OSMTs but also with regards to the transferability of this concept to other contexts such as OSH in general.

The authors anticipate that this first overview will lead to more structured research approaches of future OSMT build workshops and subsequently to an incremental improvement of these workshops so that they can eventually form an important contribution to the spread of OSMT and the open-source hardware concept. Additionally, this paper also bears important inputs for OSH replicability in general.

With regards to the participants' learning journeys towards obtaining technological literacy: of course, the hypothesis of a holistic approach strengthening technological literacy to a different level has yet to be further pursued and validated. However, first results show that the workshops are already highly successful when it comes to participants using their built machines at the end of the workshops and coming up with their own suggestions of improvements.

However, the authors also suggest future research to focus more specifically which phases mainly refer to which level of technological literacy in order to be able to specifically target certain aspects of technological literacy within the build workshop and to specifically adapt the workshops to certain target groups.

Also, the follow up of the learnings and takeaways from the workshops should be further institutionalized to gain a deeper understanding on the interconnection of the workshop flow and individual learning journeys.

This paper is merely a first step of grasping the OSMT replicability and community engagement. Within the further course of this project, the workshops will be analyzed and depicted more thoroughly to further enhance the understanding of OSH replication process and its effect on participants' technological literacy.

ACKNOLODGEMENT

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project "Fab City Hamburg"].

REFERENCES

[1] C. and T. (European C. Directorate-General for Communications Networks *et al.*, *The impact of open source software and hardware on technological independence, competitiveness and innovation in the EU economy: final study report*. LU: Publications Office of the European Union, 2021. Accessed: Sep. 21, 2022. [Online]. Available: https://data.europa.eu/doi/10.2759/430161

[2] J. Pearce, 'Impacts of Open Source Hardware in Science and Engineering', *The Bridge*, 2017, Accessed: Sep. 13, 2022. [Online]. Available: https://hal.archives-ouvertes.fr/hal-02111398

[3] S. Spaeth and P. Hausberg, 'Can Open Source Hardware Disrupt Manufacturing Industries? The Role of Platforms and Trust in the Rise of 3D Printing', in *The Decentralized and Networked Future of Value Creation: 3D Printing and its Implications for Society, Industry, and Sustainable Development*, J.-P. Ferdinand, U. Petschow, and S. Dickel, Eds. Cham: Springer International Publishing, 2016, pp. 59–73. doi: 10.1007/978-3-319-31686-4_4.

[4] J. M. Pearce, 'Cut costs with open-source hardware', *Nature*, vol. 505, no. 7485, Art. no. 7485, Jan. 2014, doi: 10.1038/505618d.

[5] K. Balka, C. Raasch, and C. Herstatt, 'Open source enters the world of atoms: A statistical analysis of open design', *First Monday*, Nov. 2009, doi: 10.5210/fm.v14i11.2670.

[6] J. M. Pearce, 'Emerging Business Models for Open Source Hardware', Social Science Research Network, Rochester, NY, SSRN Scholarly Paper ID 3331121, Mar. 2017. Accessed: Nov. 25, 2021. [Online]. Available: https://papers.ssrn.com/abstract=3331121

[7] C. Andersen, *Makers - The New Industrial Revolution*. London: Random House Business Books, 2012.

[8] G. Niezen, P. Eslambolchilar, and H. Thimbleby, 'Open-source hardware for medical devices', *BMJ Innov.*, vol. 2, no. 2, Apr. 2016, doi: 10.1136/bmjinnov-2015-000080.

[9] L. Winter *et al.*, 'Open Source Medical Devices for Innovation, Education and Global Health: Case Study of Open Source Magnetic Resonance Imaging: Reshaping Business and Society in the Era of Bottom-up Economics', 2019, pp. 147–163. doi: 10.1007/978-3-319-97788-1_12.

[10] M. Moritz, T. Redlich, S. Günyar, L. Winter, and J. P. Wulfsberg, 'On the Economic Value of Open Source Hardware – Case Study of an Open Source Magnetic Resonance Imaging Scanner', *J. Open Hardw.*, vol. 3, no. 1, Art. no. 1, May 2019, doi: 10.5334/joh.14.

[11] *Open Source Product Development*. Accessed: Sep. 21, 2022. [Online]. Available: https://link.springer.com/book/10.1007/978-3-8349-6949-1

[12] J. Pearce, 'The case for open source appropriate technology', *Environ. Dev. Sustain.*, vol. 14, pp. 425–431, Jun. 2012, doi: 10.1007/s10668-012-9337-9.

[13] T. Redlich and J. P. Wulfsberg, *Wertschöpfung in der Bottom-up-Ökonomie*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011. doi: 10.1007/978-3-642-19880-9.

[14] 'https://www.oshwa.org/definition/', *OSHWA*, 2022.

[15] J. Bonvoisin, R. Mies, J.-F. Boujut, and R. Stark, 'What is the "Source" of Open Source Hardware?', *J. Open Hardw.*, vol. 1, no. 1, Art. no. 1, Sep. 2017, doi: 10.5334/joh.7.

[16] 'DIN SPEC 3105-1:2020-07, Open Source Hardware_- Teil_1: Anforderungen an die technische Dokumentation; Text Englisch', Beuth Verlag GmbH. doi: 10.31030/3173063.

[17] 'DIN SPEC 3105-2:2020-07, Open Source Hardware_- Teil_2: Community-basierte Bewertung; Text Englisch', Beuth Verlag GmbH. doi: 10.31030/3173062.

[18] J. Bonvoisin, J. Molloy, M. Haeuer, and T. Wenzel, 'Standardisation of practices in Open Source Hardware', *J. Open Hardw.*, vol. 4, no. 1, p. 2, Aug. 2020, doi: 10.5334/joh.22.

[19] M. Omer, M. Kaiser, M. Moritz, S. Buxbaum-Conradi, T. Redlich, and J. P. Wulfsberg, 'Democratizing Manufacturing – Evaluating the Potential of Open Source Machine Tools as Drivers of Sustainable Industrial Development in Resource Constrained Contexts', pp. 256–266, 2022, doi: 10.15488/12154.

[20] R. Antoniou, R. Pinquié, J.-F. Boujut, A. Ezoji, and E. Dekoninck, 'IDENTIFYING THE FACTORS AFFECTING THE REPLICABILITY OF OPEN SOURCE HARDWARE DESIGNS', *Proc. Des. Soc.*, vol. 1, pp. 1817–1826, Aug. 2021, doi: 10.1017/pds.2021.443.

[21] R. S. Davies, 'Understanding Technology Literacy: A Framework for Evaluating Educational Technology Integration', *TechTrends*, vol. 55, no. 5, pp. 45–52, Sep. 2011, doi: 10.1007/s11528-011-0527-3.

[22] J. W. Hansen, 'To Change Perceptions of Technology Programs', *J. Technol. Stud.*, vol. 29, no. 2, May 2003, doi: 10.21061/jots.v29i2.a.10.

[23] T. Diez and F. C. G. Initiative, 'Fab City Whitepaper', p. 11, 2016.

[24] U. Flick, *Introducing Research Methodology: A beginner's guide to doing a research project*. Sage, 2015.

Fab City Hamburg: A living lab approach to explore new forms of open, distributed manufacturing in an urban context

Sonja Buxbaum-Conradi*, Jana Koppe, Manuel Moritz, Tobias Redlich, Jens P. Wulfsberg
Helmut-Schmidt-University
Hamburg, Germany
*buxbaum-conradi@hsu-hh.de

Abstract – **Within the present paper we illustrate how the living lab approach has been operationalized, in order to establish a real life experimental urban setting in which open distributed manufacturing concepts (ODM) can be tested and further developed and investigated. The living lab approach is a type of transdisciplinary, participatory action research, which aims at creating user-centered, iterative, open innovation ecosystems that integrate concurrent research and exploration processes within a public-private-people partnership. We focus on the geographical area of the metropolitan region of Hamburg that has recently become a so-called Fab City as part of a global association and network of cities that share the common goal to *produce a good part of its needed products locally.* This makes it a particularly interesting case to empirically explore and theoretically conceptualize not only open distributed manufacturing, but more general emerging forms of cosmo-localist approaches to (re-)industrialization.**

Keywords – distributed manufacturing, open production, living labs, cosmo-localism, urban transformation, open source hardware, local production sovereignty

I. Introduction

As part of the globalisation and diversification of supply chains, the last decades have seen a significant offshoring of manufacturing and further specialization along value chains towards knowledge intense processes, servitization and data based business models in so-called advanced economies [1]. This development has fostered global integration, but at the same time established strong interdependencies and unequal developmental outcomes with massive ecological consequences. It has also led to a lack of awareness, knowledge and last but not least control of how and by whom the things we use and consume in our daily lives are actually made and where they come from. This counts especially for the urban space and its continuous increase in consumption and the amount of material resources needed for their sustenance.

Meanwhile, events such as the COVID-19 pandemic, increasing international tensions and conflicts and the overall ecological crisis have shown that the complex structure of globally integrated production networks is quite fragile and susceptible to external shocks and disruptions [2, 3]. Production shutdowns, component shortages, shipping disruptions and export controls have led to a growing uncertainty as well as rising transaction costs pushing firms around the world to reconfigure their global-spanning value chains. According to some authors this will 'ultimately lead to a more regional and less globalized world economy.' [4]

As a consequence, the current system of global economic integration and its dependence on capitalist models has been increasingly put into question. Critique on existing globalized production models becomes for instance apparent in a growing activism (e.g. around the G8 and G20 summits, Fridays for Future, etc.) and emerging public debates across the entire political spectrum [5]. These debates - whether among researchers or within society in more general - are linked through their strong emphasis on prevailing and **new forms of localism** and their request for alternative production models.

Although potentials for reshoring and **(re-) industrialization** have been existing before, it was certainly the pandemic that put them in the focus of interest [6]. Simultaneously, concepts of open source hardware and an exponential growth in related projects and open makerspaces in different domains are providing easy access to knowledge and small-scale production means on a local level. This is increasingly recognized by industrial actors and policy makers in terms of independence, resilience and innovation in the EU economy [7]. In order to protect environmental wellbeing, local industries and the resilience of communities, old notions such as protectionism, autonomy and self-sufficiency have been revived and found their way into current debates. As a consequence, questions of local industrial capacities and the future of local manufacturing sectors are gaining more academic as well as public interest.

Researchers have been for instance investigating cases of local food sovereignty and alternative food networks or local textile production [8]. However, less attention has hitherto been placed on what might be described as a type of ***local production sovereignty*** and alternative production models that relate to the strong global interdependencies in the manufacturing sector evident across many goods and commodities.

https://doi.org/10.24405/14534

Scholars investigating post-industrial paradigms in the field of economics, engineering and innovation have predominantly stressed the decoupling of growth from material (and human) resources (e.g. through, digitalization, platformization/ servitization) as well as from the idiosyncrasies linked to its local embedding (see for ex. [9]). We argue that one major inaccuracy of these assumptions and related imaginations of a fourth industrial revolution lies in its (assumed) dematerialization of value creation. In most of the economic literature, so-called advanced economies in the Global South are based on knowledge, information and service orientation driven by an almost innate need to constantly innovate. The endless stream of commodities and goods traveling across the globe seem to have been flowing so steadily and reliable that only recent events have really reminded us of our dependency on material things, on goods and raw materials shipped in mostly from the Global South. It is time not only to bring 'the local' back into the debate but also to (re-)introduce 'the material' into the analysis, especially when it comes to environmental well-being.

The point here is not to trap into naïve categories of the local, but instead to focus on **concrete strategies proposed for (re)locating production** that neglect neither its material manifestation nor its multi-dimensional global interweavings. Hence, going beyond existing approaches, it is worth – and by all means necessary - examining a broader, more plural space of economic possibility and pay attention to alternatives that have previously not been on the radar [10].

Within the present paper we introduce an extensive real life experiment in which we focus on one particular upcoming strategy of re-industrialisation and re-localization of manufacturing that is based on a cosmo-localist approach to ideas of community-oriented, open production models. Although not a coherent concept yet, in the field of production engineering and supply and operations management it is predominantly referred to as **distributed manufacturing (DM)** [11] [12] or open production [13]. DM describes a post-fordist production model (quite in opposition to traditional mass production) that basically relies on a network of loosely coupled micro production units that enable local production on demand.

After an introduction of the central underlying concepts and its already existing instantiations, we outline the major challenges that come along with the actual realization of such production models and the lacking empirical evidence regarding major claims and promises made by authors and advocates of the approach. This serves as a basis to deduct key research questions that will be addressed in the subsequent empirical analysis operationalized within a living lab research framework designed around the metropolitan region of Hamburg that has recently become the first so-called Fab City in Germany pursuing the ambitious goal of producing almost everything that is consumed locally by 2054.

II. Theoretical and Conceptual Framework

Design GLobal, Manufacture Local: The promises of distributed manufacturing and cosmo-localism for circular urban production models

The following paragraph introduces the theoretical and conceptual framework as well as the rationale underlying the strategy of re-industrializing urban spaces based on a cosmo-localist approach to community-oriented, open production models that are aiming to establish small-scale regional economic cycles.

Cosmo-localism, Distributed Manufacturing and the free circulation of design ideas

Around the overall growing discourse on reshoring, re-industrialization and the relocalization of production and manufacturing different strategies have emerged in order to meet the above outlined challenges. Among them is a cosmo-localist approach that basically suggests 'the mutualization of planetary knowledge for use in localized production, solutions and development, to support positive social and ecological goals.' [14]

Cosmo derives from the Greek word for universe. Hence, cosmo-localism (a neologism created from 'cosmopolitan localism') explicitly addresses interactions and interdependencies between different spatial scales, actors and resources distributed around the globe.

The main ideology and vision behind cosmo-localist approaches to value creation (and manufacturing in more particular) is to reduce the global circulation and movement of material goods (i.e. atoms) by simultaneously enabling or facilitating the international circulation and transfer of designs, ideas and knowledge (i.e. bits) on how to realize and produce these ideas locally [15]. In doing so, it prioritizes a more pluriversal conception of autonomy and creativity trying to avoid the development of universal solutions to local problems [14, 16].

A more concrete operationalization of the concept can be found – though under different notions – in discussions and research on distributed manufacturing systems [12, 17–21].

Opposed to conventional mass production in a few very large production sites, DM relies on a network of loosely coupled actors providing micro production units that can offer local (customized) production on demand. It is basically enabled by advanced manufacturing technologies in the field of additive manufacturing (commonly known as 3D-printing) and the digitization of design, construction (CAD) and manufacturing tools (CAM/ CNC) in more general that have become more accessible and affordable during the last decades [11].

DM is associated with several positive outcomes most notably the reduction of logistics (i.e. transport), and shortening of process chains (e.g. through additive manufacturing), which will lead to a reduction of traffic, pollution and energy [22, 23]. In the field of production engineering, the potential of the model has been hitherto mainly discussed and validated in the context of emerging markets and early stages of industrialization in less industrialized areas or areas which are otherwise less attractive for manufacturing plants due to their remote location. This is also the reason why the concept is increasingly acknowledged and applied in the field of development cooperation. DM is estimated to foster social sustainability (e.g. higher employment rates), increase innovative capacities, foster local development and lead to an overall more sustainable long-term development and societal benefits that are valuable for both industrial and public/ institutional actors (for instance on the municipal level of cities [22–24]).

However, DM is not a coherent concept yet, and its actual realization in the industrial sector remains partly unclear until today. There are indeed different types of DM that can be basically distinguished along the following dimensions:

- the degree of openness
- the degree of consumer involvement
- the degree of vertical integration of activities
- the degree of formalization
- the degree of scalability (economies of scope versus economies of scale)

In its most extreme form, DM relies on prosumers (a neologism that designates the blurring boundaries between producers and consumers) often organized in globally dispersed virtual networks that engage in peer-to-peer production relationships enabling the 'personal fabrication' of goods on a small-scale local level. In this case there is a maximum level of openness (no conventional IP protection/ designs are open source) and maximum consumer involvement (i.e. consumers become producers). Activities are not vertically integrated, but instead decentralized and often self-organized in heterarchic networks. Thus, technologies, interactions and transactions are characterized through a low level of formalization and standardization. We refer to this form as ***the open, distributed manufacturing model (ODM)*** in the following. In practice there already emerged small ODM networks for instance in cases of community-based locally initiated production of protective equipment such as face shields [25]. These new patterns of building up (ad hoc) manufacturing capacities locally also took place in Hamburg.

On the other end of the continuum, less 'extreme' forms of DM can be aligned with mass customization [26]. Here the producer remains in control over the degree of consumer involvement. IP is more conventionally protected and it can be scaled up easily showing a tendency towards modular and batch production [12], which is based on high levels of standardization and formalization. In theory, between these two ends of the continuum, multiple configurations and expressions of DM are possible that range from an orientation towards degrowth models to forms of distributed capitalism and building a fertile ground for further exploration and research.

Cosmo-localist approaches to production can be classified as a specific expression of ODM since they are intrinsically linked to commons-based and alternative open-source modes of production (e.g. open source hardware). In this stream of literature**,** ODM is associated with the empowerment of people to 'democratize' production and gaining back power over local production and consumption practices. This is also the reason why it is increasingly associated with economic degrowth trajectories [27] and has been adopted by activists and social movements that criticize existing capitalist growth-based models of the economy.

> *DGML describes the processes through which design is developed, shared and improved as a global digital commons, whereas the actual manufacturing takes place locally through shared infrastructures with local biophysical conditions in mind.* [28]

Hence, in the core of this approach lies the conjunction of open source and open design and production logics at the global scale with local-network production capabilities at a regional scale [29]. In practice this means, that beyond traditional IP frameworks, designs are not protected, but are open and can be shared through different license models (e.g. creative commons) that have been established in the recent decade. Compared to developments in software development, open source hardware (OSH) projects and related online communities have evolved in various fields of technologies and applications ranging from medical devices [30] to land machines, drones, consumer products, cargo bikes and automotives. People distributed around the globe coming from very heterogeneous backgrounds (from students, to professionals, consumers, researchers and designers) virtually gather to develop, revise, improve and freely share hardware designs and documentation [30]. According to the underlying license model, the may also build, adapt, use and sell physical artefact based on these open designs.

Whereas Open Source Software is a well-established phenomenon, practitioners are still in an experimentation phase when it comes to the economic 'value' of OSH. However, recent case studies could generate further insights into these alternative modes of knowledge sharing in value co-creation and identify new business models in this field [30–32].

In the context of building up local manufacturing capacities, one promising approach is the development of standardized open source machine tools [33] that enable easy replication, modification and adaptation through standardized, modular architecture and can consequently be the basis for building low-cost local manufacturing capabilities and a technical infrastructure for manufacturing.

Although there are different approaches to DM (from more open community-oriented/ commons-based small-scale approaches to large-scale operations in the field of mass customization), there seems to be consensus on what predominantly enables them at least from a production engineering perspective. It is the interplay between 'infrastructural provisioning and network configuration, which determines the development and performance of localized production models.' [12] There is consensus that DM requires lower investment in physical or cyber-physical infrastructure as previous forms of so-called advanced manufacturing (e.g. I4.0, IoT) [34, 35]. DM production networks and start-ups require considerably less capital investment due to shared infrastructures and due to their ability to shorten development, design and product testing time as well as the fact that they do not need complex supply and distribution chains [34].

Associated technologies can be low-cost, easy-to-use and adjustable to local needs making them feasible for small-scale operations and potentially enable people to 'become more autonomous by controlling the manufacturing of their means of production' [27]. This could be accelerated by affordable, standardized open source machine tools that can be easily replicated.

Taken together, ODM bears the potential to promote what has been earlier referred to as a form of ***local production sovereignty*** through providing cyber-physical infrastructures for manufacturing on which local value chains can be build and related production networks can evolve. However, besides a local physical infrastructure for manufacturing (that can be certainly achieved with far less capital investment), what has been much less in the focus of scholars in this field is the digital infrastructure that ideally enables both: the operation of DM at the local scale with minimal transaction costs, as well as the development and sharing of design ideas and knowledge on a global scale. What comes closest to this necessary emerging (cyber-physical) infrastructure in the existing literature can be partly found in the concept of smart cities [35].

In most of the sources, the imagination of cosmo-localism as well as the potential associated with DM is indeed linked to the urban [36]. The last section of this chapter intends to introduce the Fab City movement and briefly discuss the potentials of ODM for urban strategies of transformation towards self-sufficiency and circularity.

III. Urban Transformation and the Fab City Movement

Cities are considered to be the main sites and drivers of economic growth and at the same time they produce 50% of the world's waste, 80% of the world's pollutant gases while consuming 75% of natural resources. Cities still rely predominantly on linear production models based on a massive energy consumption and lacking waste recovery [37]. Since urbanization is growing rapidly assuming that 68% of the world's population will live in cities by 2050 [38], policy makers are seeking for strategies that enable circularity as well as the resilience of cities. In search for solutions to foster circular economy the focus of most studies and approaches is on the reuse and repair of products, the reduction of consumption as well as the recycling of materials [39]. Less attention has hitherto been put on questioning the current global economic integration and modus operandi of complex global production networks. Exceptions can be mainly found in the agricultural production and food supply or the textile and fashion industry. Whereas the concepts of smart and resilient cities have different roots they seem to increasingly intertwine [40]. Originally the concept of smart cities has been pushed by large tech companies (Cisco, IBM, Philips) starting around 10 years ago to promote the deployment of ICT as a driver for economic growth and competitiveness. In contrast, the concept of resilient cities has been mainly promoted by international organizations and associations to strengthen a city's capability to respond to natural hazards (e.g. hurricanes, floods, tsunamis). Nowadays, both concepts have evolved into a rather multi-objective and participatory strategy that aims at tackling environmental deterioration and other external shocks while trying to foster sustainability, inclusion and building social capital [41].

The Fab (Fabrication) City ideology and movement combines insights and issues from the three dominating strategies for urban transformation: circular, smart and resilient cities. Proponents of the Fab City aim to radically transform how cities meet their needs and produce for themselves, while at the same time facilitating a global community of designers and makers [16]. According to them, Fab Cities bear the potential to support 'the development of localized circular economies that can transform the waste system and waste paradigm'. This is estimated to support 'cities and regions in becoming auto-productive, to form complex cosmo-local value chains for greater resilience' and keep 'production within planetary boundaries' [14].

In order to better understand the aspirations and rationale behind the Fab City concept, we briefly summarize its origins in the following section.

Origins and visions of the Fab City movement

Fab City is basically a spin-off of the FabLab movement initiated by MIT's Centre for Bits and Atoms around the beginning of the millennium. Neil Gershenfield's famous class on 'How to make almost anything' in 1998 was the starting point for an educational movement that aims at providing engineering knowledge and expertise to everyone. It resulted in the founding of the Fab Foundation which over the years fostered the development of at least 1.500 open workshops for manufacturing, so-called FabLabs, in over 90 countries as well as a globally distributed educational programme called the Fab Academy [42].

Fab City originated in 2014 during FAB10, the 10th global annual reunion of the Fab Labs network and has been issued by IAAC, MIT's Centre for Bits and Atoms, the Fab Foundation and the Barcelona City Council. Given its origins in the field of engineering, it is marked by a strong techno-optimism that ascribes transformative potentials to technologies, although actually following a community- and human-centered approach. During the last 8 years it evolved into a global association that has gathered 44 cities and regions under the common vision of becoming auto-productive by 2054. This ambitious goal should, however, rather be interpreted as a symbolic (motivating) vision than a realistic achievable goal. It is pushed forward through local communities within the participating cities, which are connected globally and meet annually face-to-face at a week-long global summit.

In order to become a part of the network (i.e. a Fab City) one has to gather a consortium consisting of local FabLabs, start-ups and other third parties integrating at least local municipalities (e.g. the mayor of the City, the Senator for economy etc.). In 2018, exactly 20 years after Neil Gershenfields' class on 'How to make almost anything' the publication of 'Fab City: Mass distribution of (almost) everything' [43] has been launched presenting best practices from the existing network including digital technologies such as blockchain and artificial intelligence. This is probably also why it has been increasingly interpreted as a critique on and alternative to existing conceptualizations of 'smart cities' [44]. Here, it becomes particularly apparent that the initial idea of technological empowerment of citizens in terms of 'making things' (i.e. manufacturing) has emerged into a project that aims to redistribute the power of monitoring and control over a territory 'by democratizing advanced technology, and enabling networking of users in a digital space.' [45] As a result, it has meanwhile grown into an initiative that aims to 'redefine common grounds for citizenships, helped by technology' [45].

However, in its actual manifestation each city seems to follow a quite unique strategy and interpretation of what it considers to be a Fab City building on different networks, institutional settings and trajectories of how they have come into being. The Fab City Hamburg initiative is strongly influenced by manufacturing and open source production ideologies connecting thematically to the origins of the movement.

Key research interests and dimensions of the project

The overall goal of our research programme is to gain empirical insights into the technologies, governance, institutional framework, material, and value flows of the open production model suggested in the prior sections. The gained knowledge can serve as a basis for developing a more coherent multi-dimensional framework and advance existing technologies and the processes used to create them.

The main aims of the development of the prototypical Fab City setting in Hamburg (on a more strategic managerial level) is to set a breeding ground for innovation in community-oriented manufacturing and urban production by building a physical (i.e. technical) infrastructure, local networks and communities and promoting knowledge transfer and education. Hence, in terms of urban transformation and setting up a real life experiment key research interests lie in optimal citizen and user involvement, diffusion (of innovations) and business models, legal issues (liability and licensing models), educational formats and urban transition governance.

Whereas research questions, interests and outcomes within the entire project are distributed among different disciplines and dimensions, they are all somehow linked through their striving for innovation and change. The overall project can therefore be placed in the field of open innovation studies choosing an open collaborative approach to public private sector innovation and institutional change as the following paragraph will show. The presented case is particularly suitable for investigating the iterative cycles in which top-down strategies (i.e. the ambitious vision of becoming an auto-productive, circular city with regional economic cycles) adapt to bottom-up answers in a very open heterogeneous setting. The principal openness in terms of networks, IP and knowledge sharing is considered a fertile ground for the development of fitting solutions and future models and the engagement of a variety of societal actors.

Thus, the Fab City Hamburg project is both a research and a development project. The focus of the given paper is on the more practical topic: the development and implementation of the prototypical Fab City setting. Here, we primarily focus on how emerging forms of ODM can be promoted and further explored in Hamburg. Or in other words: how can we create spaces for innovation, exploration, dialogue and co-creation engaging a broad already existing community in Hamburg and abroad? The focus in terms of implementation lies in promoting and gaining knowledge on:

- the establishment of a physical infrastructure for ODM through developing modular, standardized open source machine tools and how to foster their diffusion and adaptation,
- local networks and the development of local value chains,
- local/ regional economic life cycles, local sourcing, recycling and repair,
- promoting capabilities and knowledge transfer (education).

This comes along with several more practical oriented questions such as:

- Who are the actors that already provide small-scale open production sites in the city of Hamburg?
- How can they be connected and institutionally integrated?
- How can they be supported in building up local manufacturing capabilities in terms of ODM (technically, financially and institutionally)?
- What kind of sectors and fields of action are particularly suitable?
- What kind of products and services can be created in an ODM context?

Methodology and Operationalization

In order to examine how the premises of the cosmo-local distributed manufacturing approach can be realized in practice and to clarify how or if it can transform or at least contribute to new forms of urban value creation we build a real life experiment based on the living lab approach. In the following section we introduce the approach and illustrate how it has been operationalized in the given case study. Since the study is still in a preliminary stage, we conclude with some reflections on challenges as well as an outlook that outlines key questions for future research.

IV. Participatory Action Research and the Living Lab Approach

The COVID-19 pandemic has highlighted the importance of open, collaborative approaches to private as well as public sector innovation that involve a variety of different stakeholders to co-create solutions in order to find economic alternatives and alternate production models that help to rethink current economic principles and revive the economy [46] . In this context, Living Labs (LL) have gained increasing attention and have become a popular approach to collaborative innovation [47] as well as urban transformation [48, 49] among scholars, practitioners and policy makers (see for ex. the European Network of Living Labs/ EnoLL).

Living Labs can be classified as a participatory action research paradigm, since they emphasize participation as well as action by communities directly and indirectly affected by that research seeking to understand the world by simultaneously trying to change it collaboratively. It relies on collective inquiry and experimentation that is grounded in experience [50] and hence demands for a qualitative research methodology that focusses on exploration rather than hypothesis testing.

There currently exist many different definitions and approaches to LLs. We rely predominantly on literature from the field of innovation management focussing on collaborative innovation, user-centered design [51] as well as urban studies that are most suitable to our extensive case study focussing on the Metropolitan region of Hamburg and the innovation strategy behind making Hamburg a 'Fab City' through enabling and promoting DM infrastructure and practices.

Thus, following Westerlund et al. [52] we consider LL as platforms providing shared resources (i.e. physical and digital infrastructure for small-scale DM approaches). These platforms or innovation eco-systems bring together a variety of private and public stakeholders (i.e. FabLabs, Makerspaces, SME, municipalities, researchers, users, citizens, NGOs) to gather, create, communicate, and deliver new knowledge. Within this public-private-people partnership existing and developed concepts, products, services and processes can be explored and validated, in order to 'facilitate professional development and social impact in real-life contexts.' [47] The outcome or 'product' of a living lab can have very different forms ranging from objects, to services, technologies, applications, processes or systems.

In terms of operationalization (especially in a more research than practice oriented perspective), LL is a multi-method approach that combines methods and tools originating from the fields of ethnography, sociology, psychology and strategic management, design science and engineering. In our case, the LL field trial is both a technological as well as a social experiment that makes it a testbed as well as an ethnographical research setting in which processes of socio-technical co-creation can be observed [53]. The focus is on exploring (and evaluating) the prototypical realization of ODM in the Fab City Hamburg context from a multi-dimensional perspective. Hence, our lab approach is not intended and designed to foster urban transformation in the first place. The impact of LL on processes of urban transformation is probably quite limited [54]. Our LL is mainly designed to investigate and advance processes and practices of emerging forms of ODM.

Building a living lab initiative in a more practical sense, is a challenging endeavour. Depending on the specific problem a living lab initiative wants to explore and seek a solution for, there exists a variety of different approaches how to practically establish and manage an LL setting. We rely mainly on the suggestions made by Steen and van Bueren [55]. As opposed to the conventional organization of living labs around the development of a particular innovation they suggest that living labs can be also designed around a 'geographical area that forms the arena for multiple living labs focusing on various problems.' [55] In such place-determined projects multiple single lab initiatives are connected by a platform that can be a fertile ground for innovation. The main challenge here is to really assure stakeholders engagement and integrate single activities into a coherent framework and platform. The development can be roughly divided into 8 phases within a generally iterative development cycle shown in FIGURE 1.

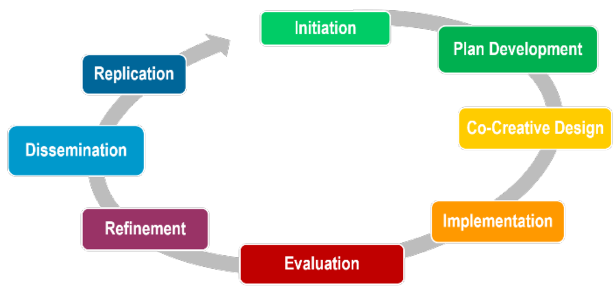


FIGURE 1: LL DEVELOPMENT CYCLE.

Since the project is still in a preliminary stage, we focus only on the first stages here. In the initiation phase, problems that the LL wants to find solutions for are defined and fitting partners (inclusion of the right capabilities) and places for realization are identified. In the second stage of plan development, shared visions and process design are developed together in a co-creative iterative process and an appropriate management structure and work flows are established.

A lot of participants in LL initiatives contribute to innovative co-creation work and activities on a voluntary basis. Therefore, participants cannot be managed in a conventional way. Instead of forming a strong hierarchical authority the development process manager(s) should carefully motivate and inspire stakeholders and focus on building trust and strong relationships [55]. Ideally, one can identify a visionary leader that is already engaged in the community and that is moreover able to translate between the different groups of stakeholders and find a common language. The developed institutional framework should be flexible and participants should be aware of changing roles and role expectations. Last but not least, in the early development phase a suitable infrastructure for communication and sharing needs to be established.

V. BUILDING THE FAB CITY LL HAMBURG

FINDING PARTNERS AND PLACES

In the initiation phase of the given project that started already in 2017, we researched Fab Labs around the world, identified existing Fab Labs, maker and hacker spaces as well as other institutions in Hamburg and started a networking process that resulted (among other things) in the foundation of the Fab City Hamburg e.V. There are currently 21 full members ranging from NGOs, to start-ups, educational and research institutes to Fab Labs and makerspaces [56]. The association is steered by an elected management board that represents the diversity of interests of the members.

The municipal authority also supported the application of Hamburg as a Fab City committing voluntarily to its manifesto and so Hamburg became the first German city to join the global network in 2019. This set the starting point of a community building process in which various actors like SMEs, non-profit organizations, fab labs, universities and individual persons and communities have been engaged to participate and formulate a common vision and mission for Hamburg. They have been already successful in acquiring funding for own R&D projects and operation. In the given project, we are building on that existing communities, structures, projects, prototypes and networks as the heart of our LL. Open production workshops provide ideal conditions as they are spaces of mutual learning, creativity and experimentation. In this sense, the Fab City Hamburg e.V. can be considered as **an institutionalized LL platform** that links single lab initiatives distributed across the city.

Based on the overall vision, the mission statement [57] of the co-creative development process can be summarized as follows:

- Support and development of existing and new open production sites (Fab Labs, makerspaces etc.) promoting a physical/ technical infrastructure
- Development and diffusion of a digital infrastructure for collaborative design and value co-creation in the Fab City network (this project is realized with support of massive EU funding [58])
- Establishment of a Fab City Haus as a central hub for all activities carried out by the community and a prototypical testbed and demonstrator for open design and small-scale distributed manufacturing practices
- Citizen engagement and Fab City incubator programme through city wide idea challenges generating product and design ideas that are further developed into prototypes
- Development and implementation of educational formats targeting lay persons, more advanced makers, designers, companies and workers (e.g. mainly in the field of vocational trainings)
- Development of a Fab City Index relating to the Index already developed by the Fab City Paris actors. The

index aims mainly at mapping current production capacities as well as consumption and material flows, to identify gaps and potentials on the way of becoming a Fab City

To implement the mission statements, in the next steps, we identified suitable fields of action and partners providing specific practical expertise and scientific substantiation regarding our research and development goals, in order to create more specific single lab initiatives, test beds and research cases. These include:

The ***OpenLab Starter Kit*** or how to build low-cost standardized open source machine tools. In this context we develop a set of at least 12 machines out of which some have been already prototypically developed before the start of the project in formal cooperation with a start-up realized at their manufacturing site in the eastern part of the Metropolitan Region of Hamburg.

The ***OpenLab Circular Textiles*** or how to rethink textile production and consumption in Hamburg at the community-level in formal cooperation with a local textile start-up and their network partners realized in an interim temporary use of a vacant building in the centre of Hamburg.

The ***OpenLab Port*** or how to introduce advanced open source machine tools to the port industry, in order to produce unique spare parts locally on-demand realized in formal cooperation with the Hamburg Port Authority in a container lab provided by the HomePort project in the port district.

The ***OpenLab Mobile*** or how to empower local craftsmen to use digital manufacturing tools in formal cooperation with a public-private partnership institution that promotes economic and regional development in the structurally less developed southern part of the Elbe river. The OpenLab Mobile will be realized in a truck that will be equipped with several machine tools (depending on the target group) that brings the machinery in demand to the people rather than vice versa.

The ***OpenLab MedTech*** or how to enhance user innovation and knowledge sharing in the field of medical engineering and health services. This will be realized in collaboration with the Physikalisch Technische Bundesanstalt (PTB) responsible for the further development of an open source MRI technology as well as the hospital of the Federal Armed Forces in Hamburg Wandsbek that provide the physical space as well as access to users and practitioners.

The ***OpenLab Circular Plastics*** which will be realized together with an NGO in Wilhelmsburg promoting the local recycling of plastics with open source machine tools (e.g. shredding and pressing/ moulding) including people with disabilities on the shop floor.

The ***OpenLab Agri-Food*** in which we further develop and explore small-scale digital technologies like a farmbot and a wheeding bot (EcoTerrabot) developed by TUHH students on a testbed provided by the Klimaschutzstiftung e.V at Gut Karlshöhe and explore more general questions of urban food sovereignty in collaboration with partners from the Kühne Logistics University (KLU).

Last but not least, one of the most challenging parts has been the realization of the intended **Fab City Haus**. The location close to the harbour and the city centre is now a co-working space (open for the entire LL community) with a small makerspace and enough space for showcasing some of the demonstrators and products developed in other contexts. The envisioned open micro-factory (as part of the original concept for the FC Haus co-created with the commmunity) will be now realized in an adhoc pop-up factory within a to be defined interim use of a vacant building in the city.

In order to support scientific substantiation **additional research partners** have been formally integrated in the project consortium to give support in the fields of supply and operations management (KLU), innovation marketing and diffusion (Technical University of Hamburg/ TUHH), innovation-accompanying legal research (Transnational IP Center at Bucerius Law School/BLS), citizen innovation (KLU), urban transformation governance (Hafen City University/ HCU), as well as local agri-food supply chains (KLU). FIGURE 2 shows an overview of the different groups of stakeholders.

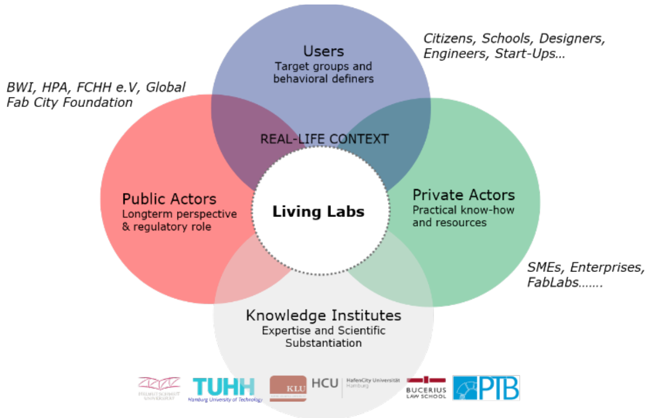


FIGURE 2: OVERVIEW STAKEHOLDERS.

Establishing a common communication infrastructure has been technically based relying on NEXT Cloud (self-hosted collaboration platform), GitLab (collaborative design), and Element (instant messaging). A common communication and PR strategy is still in the making as is the development of an efficient evaluation concept for the LLs that is able to integrate findings into a coherent framework in the end.

VI. CONCLUSION AND OUTLOOK

In the prior sections we have introduced the rationale behind theoretical and conceptual frameworks that underlie the Fab City Vision and its potentials for strategies of transforming existing practices of urban production towards more resilient, circular and community-oriented production models.

Until now, a lot of the suggestions and assumptions made by the advocates of the movement and related communities are lacking profound empirical evidence. What might be working in a small community in one specific place, cannot be easily transferred. Although the cosmo-local approach to production stresses a pluriversal solution space trying to avoid universal solutions to local problems, it still lacks a broader more consistent and empirically grounded theoretical framework. It is still a niche phenomenon; but certainly one that can widen our horizon and pave the way for exploring a more plural space of economic possibility.

In order to gain deeper empirical insights, we have chosen a LL approach to develop prototypes, processes and models that can be explored and further validated in a real-life setting. The chosen approach is likely to generate diverse insights on different dimensions of the open production model and cosmo-local approaches to (re-)industrialisation in more general ranging from technologies, governance, institutional frameworks, material, and value flows to more specific questions of citizen and user involvement, urban transition governance, legal issues and the future configuration of local value chains.

Last but not least the project is likely to stimulate learning and networking processes, foster technical literacy and awareness and create a breeding ground for innovation, new business models and the development of small-scale regional economic cycles.

Acknowledgements

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project *Fab City Hamburg*].

We also gratefully acknowledge the support of the entire project team, the Fab City Hamburg e.V. and the HSU administration that help us realizing this project.

References

1 Kleibert, J.M. (2018) Geographies of global production networks, in *Handbook on the Geographies of Globalization* (eds R. Kloosterman, V. Mamadouh, P. Terhorst), Edward Elgar Publishing, pp. 222–234.

2 Gereffi, G. (2020) What does the COVID-19 pandemic teach us about global value chains? The case of medical supplies. *J Int Bus Policy*, **3** (3), 287–301.

3 Gereffi, G., Posthuma, A., Rossi, A. (2021) Introduction: Disruptions in global value chains – Continuity or change for labour governance? *International Labour Review*, **160** (4), 501–517.

4 Ciravegna, L. and Michailova, S. (2022) Why the world economy needs, but will not get, more globalization in the post-COVID-19 decade. *Journal of international business studies*, **53** (1), 172–186, p. 173.

5 Mander, J. and Goldsmith, E. (eds) (2001) *The case against the global economy and for a turn towards localizations*, Earthscan, London.

6 Barbieri, P., Boffelli, A., Elia, S., Fratocchi, L., Kalchschmidt, M., Samson, D. (2020) What can we learn about reshoring after Covid-19? *Oper Manag Res*, **13** (3-4), 131–136.

7 European Commission, Directorate-General for Communications Networks, Content and Technology (2021) The impact of open source software and hardware on technological independence, competitiveness and innovation in the EU economy : final study report.

8 Smith, T., Ehrnström-Fuentes, M., Hagolani-Albov, S.E., Klepp, I.G., Tobiasson, T.S. (2022) Rethinking the (Wool) Economy, in *Local, Slow and Sustainable Fashion* (eds I.G. Klepp and T.S. Tobiasson), Springer International Publishing, Cham, pp. 133–170.

9 Tronvoll, B., Sklyar, A., Sörhammar, D., Kowalkowski, C. (2020) Transformational shifts through digital servitization. *Industrial Marketing Management*, **89**, 293–305.

10 Katherine Gibson, Jenny Cameron, Stephen Healy, Joanne McNeill (2019) Beyond Business as Usual: A 21st Century Culture of Manufacturing in Australia.

11 Rauch, E., Dallasega, P., Matt, D.T. (2017) Distributed manufacturing network models of smart and agile mini-factories. *IJASM*, **10** (3/4), 185–205.

12 Srai, J.S., Graham, G., Hennelly, P., Phillips, W., Kapletia, D., Lorentz, H. (2020) Distributed manufacturing: a new form of localised production? *IJOPM*, **40** (6), 697–727, p. 721.

13 Wulfsberg, J.P., Redlich, T., Bruhns, F.-L. (2011) Open production: scientific foundation for co-creative product realization. *Prod. Eng. Res. Devel.*, **5** (2), 127–139.

14 Ramos, J., Bauwens M., Ede, S.e.a. (eds) (2021) *Cosmo-Local Reader*, Futures Lab, p. 23, p.15f.

15 Kostakis, V., Niaros, V., Dafermos, G., Bauwens, M. (2015) Design global, manufacture local: Exploring the contours of an emerging productive model. *Futures*, **73**, 126–135.

16 Diez, T. (2021) Fab Cities and the Urban Transformations of the 21st Century, in *Cosmo-Local Reader* (eds J. Ramos, Bauwens M., S.e.a. Ede), Futures Lab, pp. 169–183.

17 DeVor, R.E., Kapoor, S.G., Cao, J., Ehmann, K.F. (2012) Transforming the Landscape of Manufacturing: Distributed Manufacturing Based on Desktop Manufacturing (DM). *Journal of Manufacturing Science and Engineering*, **134** (4), 11 pages.

18 Hennelly, P.A., Srai, J.S., Graham, G., Meriton, R., Kumar, M. (2019) Do makerspaces represent scalable production models of community-based redistributed manufacturing? *Production Planning & Control*, **30** (7), 540–554.

19 Kumar, M., Tsolakis, N., Agarwal, A., Srai, J.S. (2020) Developing distributed manufacturing strategies from the perspective of a product-process matrix. *International Journal of Production Economics*, **219**, 1–17.

20 Moreno, M., Court, R., Wright, M., Charnley, F. (2019) Opportunities for redistributed manufacturing and digital intelligence as enablers of a circular economy. *International Journal of Sustainable Engineering*, **12** (2), 77–94.

21 Roscoe, S. and Blome, C. (2019) Understanding the emergence of redistributed manufacturing: an ambidexterity perspective. *Production Planning & Control*, **30** (7), 496–509.

22 Rauch, E., Dallasega, P., Matt, D.T. (2016) Sustainable production in emerging markets through Distributed Manufacturing Systems (DMS). *Journal of Cleaner Production*, **135**, 127–138.

23 Kohtala, C. (2015) Addressing sustainability in research on distributed production: an integrated literature review. *Journal of Cleaner Production*, **106**, 654–668.

24 Basmer, S., Buxbaum-Conradi, S., Krenz, P., Redlich, T., Wulfsberg, J.P., Bruhns, F.-L. (2015) Open Production: Chances for Social Sustainability in Manufacturing. *Procedia CIRP*, **26**, 46–51.

25 Frazer, J.S., Shard, A., Herdman, J. (2020) Involvement of the open-source community in combating the worldwide COVID-19 pandemic: a review. *Journal of medical engineering & technology*, **44** (4), 169–176.

26 Andersen, A.-L., Andersen, R., Brunoe, T.D., Larsen, M.S.S., Nielsen, K., Napoleone, A., Kjeldgaard, S. (eds) (2022) *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems*, Springer International Publishing, Cham.

27 Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S., Schmelzer, M. (2018) Research On Degrowth. *Annu. Rev. Environ. Resour.*, **43** (1), 291–316, p. 305.

28 P2P Foundation. https://wiki.p2pfoundation.net/DGML (29 October 2022).

29 Mariscal-Melgar, J.C., Omer, M., Moritz, M., Hijma, P., Redlich, T., Wulfsberg, J.P. (2022) *Distributed Manufacturing: A High-Level Node-Based Concept for Open Source Hardware Production*, Hannover : publish-Ing.

30 Moritz, M., Redlich, T., Günyar, S., Winter, L., Wulfsberg, J.P. (2019) On the Economic Value of Open Source Hardware – Case Study of an Open Source Magnetic Resonance Imaging Scanner. *Journal of Open Hardware*, **3** (1).

31 Moritz, M., Redlich, T., Wulfsberg, J. (2018) Best Practices and Pitfalls in Open Source Hardware, in *Proceedings of the International Conference on Information Technology & Systems (ICITS 2018)* (eds Á. Rocha and T. Guarda), Springer International Publishing, Cham, pp. 200–210.

32 Pearce, J.M. (2017) Emerging Business Models for Open Source Hardware. *Journal of Open Hardware*, **1** (1).

33 Omer, M., Kaiser, M., Moritz, M., Buxbaum-Conradi, S., Redlich, T., Wulfsberg, J.P. (2022) *Democratizing Manufacturing – Evaluating the Potential of Open Source Machine Tools as Drivers of Sustainable Industrial Development in Resource Constrained Contexts*, Hannover : publish-Ing.

34 Ben-Ner, A. and Siemsen, E. (2017) Decentralization and Localization of Production. *California Management Review*, **59** (2), 5–23.

35 Kumar, M., Graham, G., Hennelly, P., Srai, J. (2016) How will smart city production systems transform supply chain design: a product-level investigation. *International Journal of Production Research*, **54** (23), 7181–7192.

36 Krenz, P., Stoltenberg, L., Markert, J., Saubke, D., Redlich, T. (2022) The Phenomenon of Local Manufacturing: An Attempt at a Differentiation of Distributed, Re-distributed and Urban Manufacturing, in *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems* (eds A.-L. Andersen, R. Andersen, T.D. Brunoe, M.S.S. Larsen, K. Nielsen, A. Napoleone, S. Kjeldgaard), Springer International Publishing, Cham, pp. 1014–1022.

37 Ellen MacArthur Foundation Circular Economy in Cities: Project Guide 2019.

38 UN Development Report World Urbanization Prospects: The 2018 Revision.

39 Ascione, G.S., Cuomo, F., Mariotti, N., Corazza, L. (2021) Urban Living Labs, Circular Economy and Nature-Based Solutions: Ideation and Testing of a New Soil in the City of Turin Using a Multi-stakeholder Perspective. *Circ.Econ.Sust.*, **1** (2), 545–562.

40 Arafah, Y., Winarso, H., Suroso, D.S.A. (2018) Towards Smart and Resilient City: A Conceptual Model. *IOP Conf. Ser.: Earth Environ. Sci.*, **158**, 12045.

41 Cañavera-Herrera, J.S., Tang, J., Nochta, T., Schooling, J.M. (2022) On the relation between 'resilience' and 'smartness': A critical review. *International Journal of Disaster Risk Reduction*, **75**.

42 Fab Foundation. https://fabfoundation.org/global-community/#:~:text=The%20Fab%20Lab%20Network%20is,in%20approximately%201%2C500%20Fab%20Labs. (29 October 2022).

43 Diez, T. (ed) (2018) *Fab city: the mass distribution of (almost) everything*, IAAC, Barcelona, Spain.

44 Rumpala, Y. (2021) 'Smart' in another way: the potential of the Fab City approach to reconfigure urban dynamics. *Urban Research & Practice*, 1–23.

45 Rigobello, A. and Gaudillière, N. (2019) Connecting Terroirs. Fab15 Research Papers, El Gouna Egypt, p. 2.

46 Chesbrough, H. (2020) To recover faster from Covid-19, open up: Managerial implications from an open innovation perspective. *Industrial Marketing Management*, **88**, 410–413.

47 Greve, K., Vita, R. de, Leminen, S., Westerlund, M. (2021) Living Labs: From Niche to Mainstream Innovation Management. *Sustainability*, **13** (2), 791, p. 2.

48 Cuomo, F. (2022) Urban Living Lab: An Experimental Co-Production Tool to Foster the Circular Economy. *Social Sciences*, **11** (6), 1–22.

49 Brons, A., van der Gaast, K., Awuh, H., Jansma, J.E., Segreto, C., Wertheim-Heck, S. (2022) A tale of two labs: Rethinking urban living labs for advancing citizen engagement in food system transformations. *Cities*, **123**, 103552.

50 Chevalier, J.M. and Buckles, D. (2013) *Participatory action research: Theory and methods for engaged inquiry*, Routledge, London, New York.

51 Tyl, B. and Allais, R. (2021) A design study into multi-level living labs for reuse and repair activities in France. *Journal of Cleaner Production*, **321**, 129032.

52 Westerlund, M., Leminen, S., Rajahonka, M. (2018) A Topic Modelling Analysis of Living Labs Research. *TIM Review*, **8** (7), 40–51.

53 Georges, A., Schuurman, D., Baccarne, B., Coorevits, L. (2015) User engagement in living lab field trials. *info*, **17** (4), 26–39.

54 Cuomo, F., Ravazzi, S., Savini, F., Bertolini, L. (2020) Transformative Urban Living Labs: Towards a Circular Economy in Amsterdam and Turin. *Sustainability*, **12** (18), 7651.

55 Steen, K. and van Bueren, E. (2017) *Urban Living Labs: A Living Lab Way of Working*, AMS Institute, Amsterdam, p. 12.

56 Fab City Hamburg Verein e.V. https://www.fabcity.hamburg/mitglieder/ (29 October 2022).

57 Fab City Hamburg Verein e.V. https://www.fabcity.hamburg/mission/ (29 October 2022).

58 Interfacer: Building the digital infrastructure for Fab Cities. https://www.interfacerproject.eu/ (29 October 2022).

Idea evaluation by citizens: The Hamburg Fab City Maker Challenge case

David Pacuku, Johanna Schnier, Tobias Redlich, Manuel Moritz, Marvin Klein, Christina Raasch, Christian Lüthje
Kühne Logistigs University, Technische Universität Hamburg, Helmut-Schmidt-Universität
Hamburg, Germany
david.pacuku@the-klu.org, johanna.schnier@the-klu.org, tobias.redlich@hsu-hh.de, manuel.moritz@hsu-hh.de, marvin.klein@tuhh.de, christina.raasch@the-klu.org, c-luethje@tuhh.de

Abstract - **Experts play an important role in the evaluation of ideas. Owing to their experience and knowledge, they are believed to be best suited to objectively evaluate ideas. At the same time, expert evaluations sometimes fail to accurately reflect stakeholder preferences. For this reason, more and more organizations have begun to solicit 'non-expert' evaluations from the 'crowd' (e.g., via community voting). We illustrate how organizations can involve stakeholders in idea evaluation in the context of the Fab City project. Integrating citizens into the innovation process is particularly interesting in a Fab City–a city that produces many of the products it needs locally–since it enables one to develop regional preferences into tailored solutions. Here, citizens evaluate a solution, implement it as a local product, and ultimately share the design (mostly open-source) within the community. In the course of a Fab City initiative in Hamburg–the Maker Challenge–citizens were invited to evaluate almost 100 innovative ideas in pairwise comparisons. We draw on over 20,000 votes from around 400 citizen judges to assess the crowd opinion formation process. Unlike in other studies, our data allow us to measure the time every citizen judge needed to make their decision. Thus, we can conclude how diligent citizen judges are and, conversely, how much attention an idea can attract. Looking at the citizen judges' evaluation times, it appears that, in most cases, the opinion-formation process is spontaneous. In a few cases, however, a substantial amount of time is spent. All the evaluation times followed a Poisson distribution. Further, we compare expert evaluations with crowd evaluations and relate the results to the literature. We conclude that the crowd evaluation process resembles the expert evaluation process. Also, we show that citizens optimize their cognitive effort over time. For real-world cases, such as the Fab City project, this implies that not only the ideation process and the implementation process can be carried out by local citizens, but also that the evaluation can be done within a community without significant loss of quality, but with much lower effort on the part of organizers.**

Keyword - Fab City–Maker Challenge, Citizen Innovation, Community Voting, Evaluation Process

I. Introduction Section

The Fab City global initiative was established in the 2010s with the aim to challenge cities whose current consumption and resource use are unsustainable. Currently, around 40 cooperating cities and regions have committed to become more self-sufficient and, therefore, more sustainable. There are different focus areas, such as food, energy, materials, waste, water, and information systems. We focus on the Maker Challenge, a local competition that invited citizens to share innovative ideas that could possibly be produced locally in the future. These ideas were then evaluated by the local population. Specifically, in Hamburg in June 2022, almost 100 innovative ideas were collected, of which the most popular 20 were implemented as prototypes with the help of experts. During this event, we collected more than 20,000 data points. The amount of data enabled us to describe the ways crowd members and experts vote on both an individual and an aggregated level.

By comparing citizens to experts, we conclude that the ways both groups vote are very similar. Coupled with the literature, we conclude that evaluation by the crowd is an appropriate substitute for evaluation by experts. Further, the Maker Challenge revealed the optimization of cognitive effort by citizens during the evaluation process.

The following chapter sheds light on the current literature and research frontiers, and forms the basis for our hypotheses, which we elaborate in chapter 3. In chapter 4, we analyze our findings, discussing them in chapter 5.

II. Literature Review

The option to outsource the innovation process to others goes hand in hand with a great many people being connected to the global network that is the Internet [1], [2]. Under the neologism *crowdsourcing*, Howe (2006) [3] describes how companies have begun to collect innovative ideas in web-based ways through consumers. These ideas are then evaluated by the crowd [4]. The practical idea behind this lies in the fact that the sheer volume of ideas collected simply cannot be handled internally without great effort. Trials to evaluate these ideas, using the resources of a firm, usually ended up being both very inefficient and time-intensive. For instance, it took Google no less than 3,000 employees and three years to evaluate 150,000 ideas submitted to its Project 10 to the 100 until the first proposals could be implemented [5]. IBM once even employed 50 senior executives for several weeks to evaluate 50,000 ideas [6].

Internal idea evaluation has not only proved inefficient, but also bears the risk of being biased. For instance, Asplund et al. (2021) [7] found that internally employed experts are biased toward exploitable ideas, owing to risk-aversion, which comes with lower uncertainty about new, innovative ideas and a preference for returns that are closer (rather than further away) in time.

For a city that has self-sustainability and resource efficiency as its goals, the possibility of outsourcing the evaluation process in the spirit of crowdsourcing seems comparable to having this evaluation done by experts [8]. The term *wisdom of the crowd* is often encountered here, defined as an observed statistical phenomenon characterized by the aggregated opinion of a population being closer to a true value than most individual evaluations, estimating for instance heights or weights [9] even though few individual votes diverge very far from the truth. Studies show a significant agreement between the crowd's opinions and experts' ratings [10] as well as overall concurrence in the relative rankings of ideas between the crowd and experts [11]. Further, Kornish

https://doi.org/10.24405/14535

and Ulrich (2014) [12] concluded that online consumer panels are even a better way to determine what is a good innovative idea than expert ratings.

Kahneman and Tversky (1981) [13] elaborated on individual errors and biases in judgment under uncertainty and define *intuition* by using it in three ways. One, an analysis can be called intuitive if it does not rely on an analytical method or a deliberate calculation. Two, a rule or a fact can be considered to be intuitive “if it is compatible with our lay model of the world.” Three, a procedure is intuitive if it is integrated into our daily living.

It is crucial to define intuition when describing the ways in which both citizens and experts evaluate innovative ideas. At some point, however, the demand for high concentration lead to effects such as cognitive overload [14]. It is also possible that participants reach their computational limits [15] and, owing to a lack of concentration, make performance errors, which limit individuals’ assessments of ideas. As a result, persons make mental abbreviations, which leads to individual biases when assessing innovative ideas.

Kahneman’s *Thinking, Fast and Slow* [16] adapts the idea of differentiated ways of thinking in a similar way. He uses the metaphor of two systems of thinking that co-exist in persons’ minds. The biggest difference between these two systems is the ways in which they are used to solve tasks or take decisions. System 1, which is the one we use most often, follows heuristic rules, and is biased, since it is characterized by an intuitive, automatic, unconscious, and effortless way of deciding. System 2, which we seldom use, is a more ‘rational’ way of thinking. It closely assesses the context and is slow, controlled, effortful, and statistical. While system 1 is mostly used to solve easy tasks in daily life, system 2 is used to solve problems in an enduring way.

Using this as a theoretical foundation, and considering the evaluation times, we hypothesize that when both experts and citizens use two different systems of thinking, this would be recognizable as a pattern during evaluation processes. Further, if this pattern is indistinguishable between citizens and experts, one can conclude that their evaluation processes are similar. This supposition is further underlined by considering the aggregated duration, where we expect to obtain comparable Poisson distributions, plotting the evaluation times against their relative frequencies (i.e., the violin density).

Further, we consider Verplanken, Aarts, and Knippenberg (1997) [17], who researched habit-based decision-making. Previous decisions that led to reasonable or positive outcomes can lead to similar behaviors, especially concerning future decisions. Further, Hoeffler and Ariely (1999) [18] concluded that this occurred most rapidly when participants had to decide between two options. This behavior can be explained by the participants’ urge to maximize the efficiency of their cognitive effort. Ariely and Zakay (2001) [19] summarized that this *preference consolidation* occurs as participants are forced to consolidate how they feel about characteristics of these ideas and forces them to stabilize these thoughts as they face tradeoffs between different ideas. Ariely, Loewenstein, and Prelec (2000) [20] drew parallels to the herding effect and call this effect–when participants internally simplify the evaluation process by using previous decisions’ characteristics–*the self-herding effect*. Taking mental abbreviations to minimize cognitive effort leads to swifter decisions if more evaluations have been carried out prior to the current one. Thus, we hypothesize that, on average, individual voters increase the evaluation process speed with the number of votes made prior.

Keeping in mind the potential susceptibilities to distortions of the wisdom of the crowd, we argue that our experimental setup minimizes potential intrusions that could lead to strongly biased voting behavior. Arguing for an unbiased dataset, we focus on the following gap in the research, asking whether, both at the individual and the aggregated levels, the ways in which citizens and experts evaluate innovative ideas are similar.

III. Methodology

Using quantitative analysis techniques, we focus on how citizens evaluate innovative ideas, so as to draw comparisons to the way experts evaluate them. We use descriptive statistics and, by depicting the dataset, we can describe the way the crowd evaluated the ideas; second, we can compare the two groups.

The data were collected in June 2022 through a unique innovation competition in Hamburg–the Fab City Maker Challenge. The challenge had three decisive steps.

First, in the spirit of a social, sustainable, innovative, and self-sufficient community, citizens were asked to share their innovative ideas by uploading them to the Challenge’s online platform. Incentives were created for the best ideas. The top 20 ideas would participate in a Prototyping Workshop, and the best idea would win a 3-D printer valued at 400 EUR. Further, more intrinsic reasons for citizens to participate were to gain publicity for their ideas through the Fab City Hamburg Maker Expo. Finally, participants could also take advantage of the community feedback in the form of comments and could improve their ideas accordingly. Overall, almost 100 ideas were submitted by a diverse group of people living in Hamburg.

To evaluate all the ideas in our campaign, we asked citizens from the broader Hamburg region to evaluate them online. The evaluation process followed the Swiss System tournament. In round 1, two innovative ideas were randomly assigned to compete against each other. The pairwise comparisons were randomly assigned to the citizen judges, who repeatedly indicated which idea they preferred or whether they considered both to be equally good. In every comparison, each idea received three points if it won, two if there was a tie, and zero if it lost. The voting system was open for about a week. Almost 20,000 evaluations were done by 400 citizens. The dataset was unique owing to the amount of information we could collect from each evaluation. By considering the anonymized data, we could retrace the duration between two evaluations, which enabled us to further characterize how the evaluation was done.

The top five ideas from the citizen evaluation process were immediately implemented in the Prototyping Workshop, while the remaining 15 (in the top 20) were distributed to experts for evaluation. The panel of experts comprised seven experts, who evaluated the remaining ideas in the top 50. In this process, 350 expert evaluations were generated.

As the citizens and the experts did not evaluate exactly the same group of ideas, we were unable to compare the respective outcomes of their evaluations of the two ideas. As per the literature, we do not expect evaluations by citizens and experts to differ significantly. Further, this set-up excluded biasing effects, such as the herding effect [21]. We focus on the ways these two groups performed in the respective tasks to evaluate these ideas.

We considered and compared, at an individual and an aggregated level, with descriptive statistics, the data we collected for both groups. Specifically, we drew the observable densities for the evaluation time for each individual and the distribution on an aggregated level. By comparing these graphics, we could then draw a conclusion about the comparability of the two groups, which differ significantly in their knowledge, experience, and expertise.

By considering the average evaluation time, conditioned on its absolute position in the rank of the consecutive evaluations, we could check whether the evaluation time decreased by rank.

IV. RESULTS

To analyze the judges' diligence in evaluating the ideas, we compared the evaluation times across the citizens. By taking the difference in time when citizen judges were exposed to a new idea and when they judged them, we could measure how much time a judge needed to evaluate it. An evaluation time was attributed to each judge and, since each judge voted multiple times, we could derive a distribution of duration for each judge. We ordered the citizen judges according to their average evaluation time, and then put them in 20 groups with the same number of judges. Next, we plotted the duration by means of violin densities to graphically illustrate the relative evaluation duration frequency. That is, the more surface a density took within a given time, the more frequently this observation has been made, see FIGURE 1 and FIGURE 2. We ran the same analysis for the expert judges FIGURE 3.

By comparing the outcomes, we drew the following conclusions: A clear pattern can be observed independently of the average evaluation time of the citizen judges; it is even observed for the expert judges: Usually, judges attempt to evaluate ideas spontaneously. Comparable to Kahneman's two systems of thinking [16], there is a pattern: the judges used their intuition to evaluate most of the ideas. This is surprising, since the two ideas given to the judges were evaluated relatively similar. In other words, even though we considered the two ideas to be very similar in quality, the judges were able to swiftly decide which one they preferred. This happened most of the time, as can be seen by the fat tails of the violin distribution at the lower end.

Further, some evaluations were not made spontaneously, as judges invested more time in evaluating some ideas. For the cases that judges did not prefer one idea over another, we provided the tie option. Thus, we could exclude that judges took longer to evaluate because they were indecisive on how to evaluate an idea. The evaluation time can therefore be considered as a measurement of the judges' diligence.

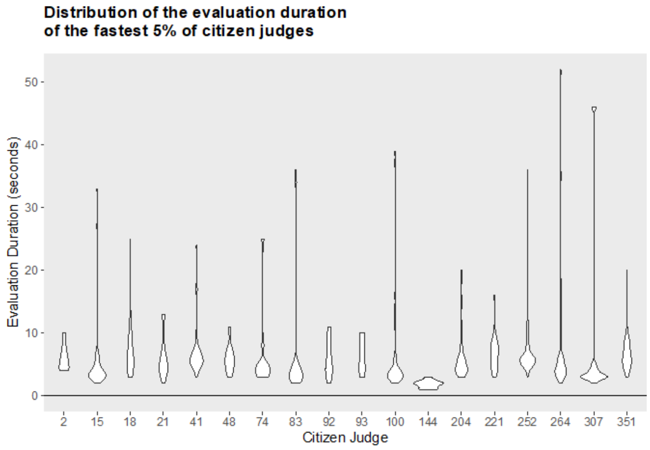


FIGURE 1: DISTRIBUTION OF THE EVALUATION TIMES OF THE FASTEST 5 % OF THE CITIZEN JUDGES.

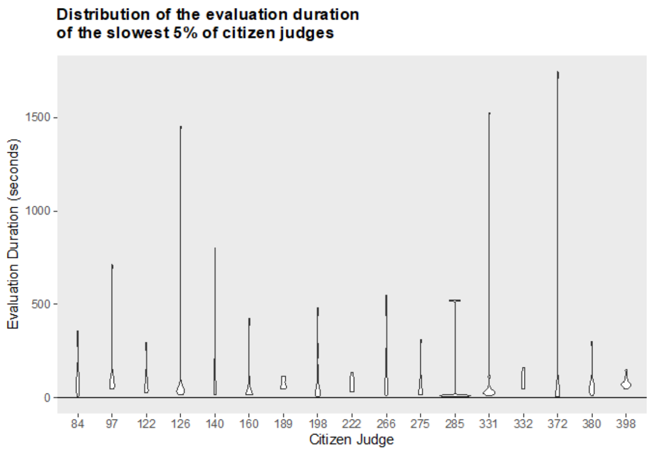


FIGURE 2: DISTRIBUTION OF THE EVALUATION TIMES OF THE SLOWEST 5 % OF THE CITIZEN JUDGES.

When comparing citizen judges to the experts, there was no difference in the patterns, in the sense that judges invested more time to evaluate some idea pairs. For most ideas, however, the evaluation time was short. Thus, the same pattern can be observed for the citizens and the experts.

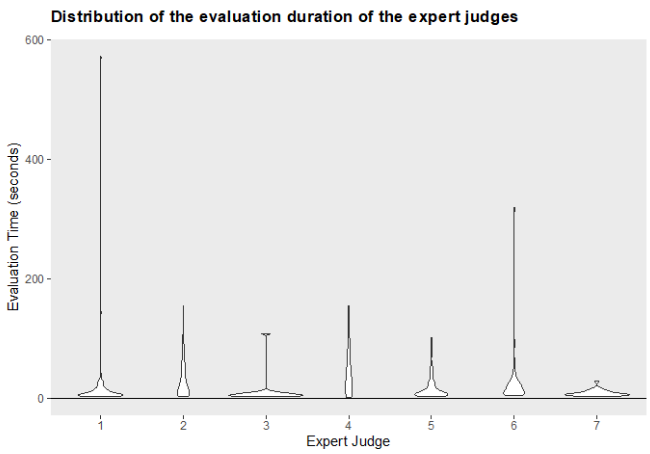


FIGURE 3: DISTRIBUTION OF THE EXPERT JUDGES' EVALUATIONS

We can observe comparable results when considering the aggregated evaluation times of the citizens, see FIGURE 4 and the experts FIGURE 5. Specifically, we obtained two comparable Poisson distributions. Both groups had a comparable evaluation time, with a mean of around 21 seconds for the citizens and around 22 seconds for the experts, which are depicted by the blue vertical dash-lines in FIGURE 4 and FIGURE 5.

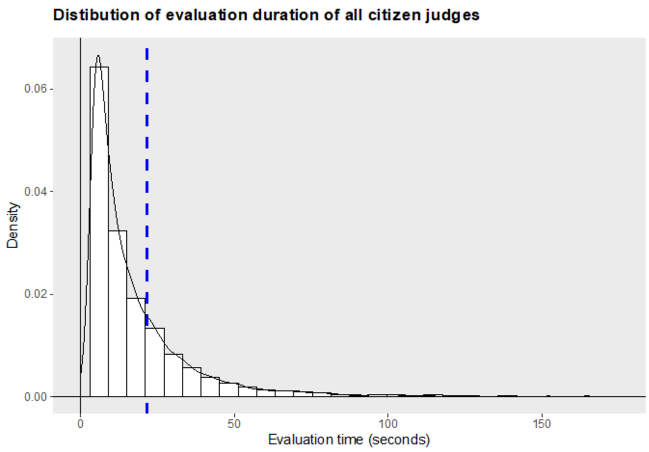


FIGURE 4: DISTRIBUTION OF THE EVALUATION TIMES OF ALL THE CITIZEN JUDGES.

As we consider the average evaluation time, given the respective rank of the evaluation, we concluded that a rank higher than 50 would lead to biased results owing to fact that we had fewer observations per rank. Thus, we excluded the evaluations ranked higher than 50 from this analysis. In FIGURE 6, one can immediately see the relationship between the ranking and the average evaluation time. The red dash-line depicts the resulting line in an OLS estimation, and the blue shadow the respective confidence interval. Driven by habit-based decisions and the intrinsic unintentional urge to maximize the efficiency of cognitive effort, one can clearly conclude that the habitus (socially ingrained habits, skills, and dispositions) reflected by the evaluation ranking plays a direct role in the evaluation time.

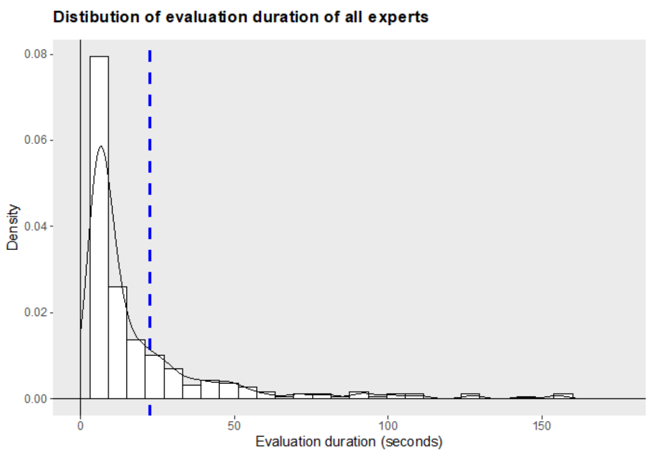


FIGURE 5: DISTRIBUTIONS OF THE EVALUATION TIMES OF ALL THE EXPERTS.

Further, notably, individual traits of both the innovative ideas and the judges played a subordinate role to no role in this analysis. Specifically, we cancelled out individual effects by

taking the average of these observations, making them comparable. This allowed us to run an easy regression, with the ranking in the evaluation frequency as the independent variable and the average evaluation time as the independent variable.

It turned out that, on average, one more ranking led to a reduced evaluation time of 0.369 seconds, which is statistically significant on all conventional significance levels. This means that, for our observation of 50 ranks, the average evaluation time decreased to around 18.5 seconds.

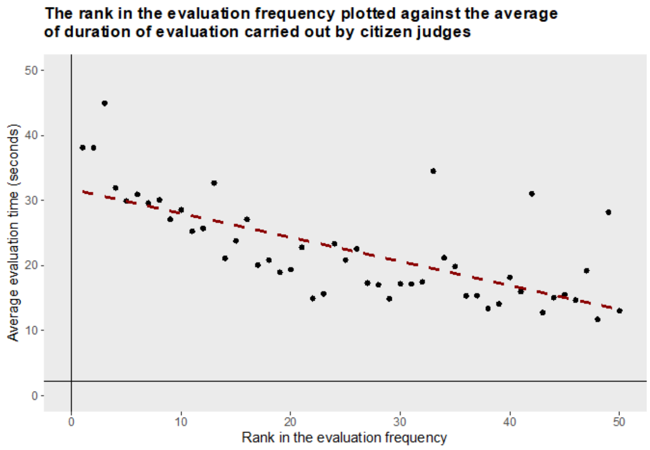


FIGURE 6: THE RANK IN THE EVALUATION FREQUENCY PLOTTED AGAINST THE CITIZEN JUDGES' AVERAGE EVALUATION TIME.

V. CONCLUSION

The idea evaluations of the Maker Challenge ideation contest provide interesting insights into the ways citizens and experts evaluate ideas. Specifically, it seems that both experts and citizens think in two different systems: spontaneous thinking and reflective thinking. The spontaneous thinking system is predominant since it reduces the cognitive effort of the evaluation process. When using the reflective system, which rarely occurs, judges–whether citizens or experts–take more time to make an evaluation. Further, aggregating the two groups' evaluation times led to almost indistinguishable Poisson distributions–another commonality between the evaluation processes of the citizens and the experts, yet only on an aggregated level. Further, looking at the citizens' average evaluation time, ranking plays an important role. The negative correlation between the rank in the evaluation process and the evaluation time can be explained by the reduced cognitive effort.

Since the comparison between evaluations by experts and citizens has been widely explored in the literature, we examined their evaluation processes. It turns out that there are strong similarities between their evaluations processes. The evaluation efforts between the two groups were not distinguishable. This confirms the feasibility of citizen-driven innovation evaluation, as fostered by Fab Cities.

ACKNOWLEDGEMENT

This paper was funded by dtec.bw (the Digitalization and Technology Research Center of the Bundeswehr), which we gratefully acknowledge [project Fab City].

References

[1] Whelan, Eoin, et al., The role of information systems in enabling open innovation., Bd. 15.11 , Journal of the Association for Information Systems , 2014.

[2] Gregori, Enrico, et al., „Smartphone-based crowdsourcing for estimating the bottleneck capacity in wireless networks,“ *Journal of Network and Computer Applications,* Bd. 64, pp. 62-75, 2016.

[3] J. Howe, „The rise of crowdsourcing,“ *Wired magazine ,* pp. 1-4, 2006.

[4] Behrend, Tara S., et al., „The viability of crowdsourcing for survey research,“ *Behavior Research Methods,* Bd. 43.3 , pp. 800-813, 2011.

[5] Blohm, Ivo, Jan Marco Leimeister, and Helmut Krcmar, „Crowdsourcing: how to benefit from (too) many great ideas,“ *MIS Quarterly Executive,* Bd. 12.4 , pp. 199-211, 2013.

[6] Bjelland, Osvald M., and Robert Chapman Wood, „An inside view of IBM's' Innovation Jam'.,“ *MIT Sloan Management Review,* Bd. 50.1 , 2008.

[7] Asplund, Fredrik, Jennie Björk, and Mats Magnusson, „"Knowing too much? On bias due to domain‐specific knowledge in internal crowdsourcing for explorative ideas.", “ *R&D Management,* Bd. 52.4, pp. 720-734, 2022.

[8] Borda, Ann, and Jonathan P. Bowen, „Smart cities and digital culture: Models of innovation,“ *Museums and digital culture,* pp. 523-549, 2019 .

[9] Mavrodiev, Pavlin, Claudio J. Tessone, and Frank Schweitzer, „Effects of social influence on the wisdom of crowds,“ 2012.

[10] Mollick, Ethan, and Ramana Nanda, „"Wisdom or madness? Comparing crowds with expert evaluation in funding the arts.",“ *Management science,* Bd. 62.6 , pp. 1533-1553, 2016.

[11] Magnusson, Peter R., Johan Netz, and Erik Wästlund, „"Exploring holistic intuitive idea screening in the light of formal criteria.",“ *Technovation,* Bde. %1 von %234.5-6 , pp. 315-326, 2014.

[12] Kornish, Laura J., and Karl T. Ulrich, „"The importance of the raw idea in innovation: Testing the sow's ear hypothesis.",“ *Journal of Marketing Research,* Bd. 51.1 , pp. 14-26, 2014.

[13] Kahneman, Daniel, and Amos Tversky., The simulation heuristic, Stanford Univ CA Dept of Psychology, 1981.

[14] C. a. C. S. Benz, „Nudged to Unload: Applying Choice Architecture to Prevent Cognitive Overload of Participants in Open Idea Evaluation,“ 2019.

[15] P. A. Klaczynski, „Heuristics and biases: interactions among numeracy, ability, and reflectiveness predict normative responding.,“ Bd. 665, 2014.

[16] D. Kahneman, Thinking, Fast and Slow, New York, 2001.

[17] Verplanken, Bas, Henk Aarts, and Ad Van Knippenberg, „Habit, information acquisition, and the process of making travel mode choices,“ *European journal of social psychology,* Bd. 27.5 , pp. 539-560, 1997.

[18] S. a. D. A. Hoeffler, „Constructing stable preferences: A look into dimensions of experience and their impact on preference stability,“ *Journal of consumer psychology ,* Bd. 8.2 , pp. 113-139, 1999.

[19] Ariely, Dan, and Dan Zakay, „A timely account of the role of duration in decision making,“ *Acta psychologica,* Bd. 108.2 , pp. 187-207, 2001.

[20] Ariely, Dan, George Loewenstein, and Drazen Prelec, „Coherent arbitrariness: Duration-sensitive pricing of hedonic stimuli around an arbitrary anchor,“ 2000.

[21] Hofstetter, Reto, Suleiman Aryobsei, and Andreas Herrmann, „Should you really produce what consumers like online? Empirical evidence for reciprocal voting in open innovation contests,“ *Journal of Product Innovation Management,* Nr. 35.2 , pp. 209-229, 2018.

Emissionsfreie GuD-Kraftwerke durch computergesteuerte stöchiometrische Verbrennung von Wasserstoff und Sauerstoff in Dampf

David Bocandé*, Nancy Kings, Markus Schatz
Professur für Strömungsmaschinen in der Energietechnik / Laboratorium für Strömungsmaschinen
Helmut-Schmidt-Universität Hamburg
Hamburg, Deutschland
*bocanded@hsu-hh.de

Kurzfassung – Die Rückverstromung von grünem Wasserstoff mittels Oxyfuel-Verbrennung in thermischen Kraftwerken ermöglicht die effiziente Bereitstellung von elektrischen Nettoleistungen im Gigawatt-Bereich. Mit Wasserdampf als Wärmeträgerfluid werden Wirkungsgrade von über 70 % prognostiziert. Um das Konzept eines H_2/O_2-gefeuerten Kraftwerks mit Dampf als Arbeitsfluid zu erforschen, wird im Rahmen des Projekts H_2 Oxyfuel, ein Mikrokraftwerk-Demonstrator aufgebaut, in Betrieb genommen und hinsichtlich der Sicherheit und Einbindung in das Energieversorgungsnetz untersucht.

Die Auslegung des Mikrokraftwerk-Demonstrators erfolgt durch thermodynamische Prozess- und Anlagenmodellierung, wobei die thermischen Belastungsgrenzen der Komponenten insbesondere der Turbine und des Abhitzedampferzeugers die Prozessparameter limitieren. Unter Berücksichtigung dieser Einschränkungen werden zusätzlich mögliche Prozesse für Großkraftwerke modelliert und bewertet.

Da bislang kein ausgereiftes Brennkammerkonzept in der Literatur beschrieben ist, werden parallel zur Prozessmodellierung auch Simulationen zur H_2/O_2-Verbrennung in Dampf durchgeführt. Basierend darauf wird im nächsten Schritt eine Brennkammer aufgebaut und experimentell untersucht. Verbrennungseffizienz und -temperatur sowie mess- und sicherheitstechnische Aspekte sind hierbei Gegenstand der Forschung. Die technische Realisierung des Mikrokraftwerk-Demonstrators erfolgt schrittweise. Zunächst wird das Arbeitsmedium für die Brennkammer prozessunabhängig über einen elektrischen Dampferzeuger bereitgestellt, welcher im späteren Verlauf partiell durch einen Abhitzedampferzeuger ersetzt wird. Um die kritischen Komponenten der Anlage gegen Versprödung und Korrosion durch Verbrennungsprodukte zu schützen, wird mit der technischen Umsetzung der H_2/O_2-Verbrennung in Dampf unter atmosphärischen Bedingungen begonnen. Sukzessive werden dann Komponenten ergänzt und der Prozess geschlossen, um mit der Integration der Turbine das Mikrokraftwerk zu finalisieren. Durch Integration des Abhitzedampferzeugers werden weitere Druck- und Leistungssteigerungen der Brennkammer möglich.

Stichworte – Oxyfuel-Prozesse, Wasserstoffverbrennung, Kraftwerksprototyp

NOMENKLATUR

BK	Brennkammer
DR	Dilution Ratio (Verdünnungsverhältnis)
DR_G	Globale Dilution Ratio
TIT	Turbineneintrittstemperatur
m in kg	Masse

I. EINLEITUNG

Wasserstoff als Brennstoff in Oxyfuel-Dampfkraftwerken ist ein Konzept, welches seit dem Ende der 70er Jahre bekannt ist [1]. Verschiedene Ausführungen wurden seitdem modelliert. Die Prozesse sind entweder vollkondensierend z.B. der Toshiba- Prozess [2, 3], oder teilkondensierend wie der Graz- [4] oder Mitsubishi-Prozess [5], wobei Prozesssimulationen zeigen, dass Wirkungsgrade von über 70 % unter gasturbinenspezifischen Bedingungen erreicht werden können.

Trotz der vielversprechenden Ergebnisse der Simulationen wurde bis heute kein solcher Prozess gebaut. Für das Arbeitsfluid Dampf fehlt bei den nötigen extremen Prozessparametern die technische und industrielle Erfahrung. Gleichzeitig stellt sich die Frage der Betriebssicherheit im Hinblick auf das Anfahrverhalten, die Regelung, Lastanpassung und die Ansammlung von unverbranntem Wasserstoff und Sauerstoff in den Kraftwerkskomponenten.

Bei der für den Prozess zentralen Brennkammer (BK) bestehen Herausforderungen hinsichtlich der vollständigen Umsetzung der stöchiometrisch zugeführten Reaktionspartner und der Vermeidung von Dissoziation [6] an Hotspots sowie Quenching [7] an kalten Oberflächen. Verschiedene Konzepte wurden bereits entwickelt [7, 8, 9, 10]. Jüngst wurde ein Brennkammer-Design mit kleinerer Leistung vorgestellt, das den Messungen der Autoren zufolge eine hohe Verbrennungseffizienz aufzeigt [11]. Eine Bestätigung der Ergebnisse steht allerdings noch aus.

Im Rahmen des Projekts soll eine Brennkammer für ein Mikrokraftwerk entwickelt und aufgebaut werden, die einen

https://doi.org/10.24405/14536

sicheren Betrieb bei Leistungen < 100 kW und Drücken bis 3 bar erlaubt. Zudem soll gewährleistet sein, dass nur geringe Mengen komponentenschädigende und gegebenenfalls zündfähige Verbrennungsrückstände im Prozess auftreten.

Zudem werden die Grenzen der technischen Umsetzung von H2-gefeuerten Oxyfuel-Kraftwerken aufgezeigt: Vor allem Belastungsgrenzen des Materials wie die maximale Turbineneintrittstemperatur (TIT) und die Temperaturfestigkeit des Abhitzedampferzeugers limitieren die Prozessparameter und damit den erreichbaren Wirkungsgrad. Zur Untersuchung des Prozesses und des Betriebsverhaltens der Brennkammer wird ein Mikrokraftwerk als Demonstrator aufgebaut, wobei die erreichbaren Drücke und Temperaturen aus Kosten- und aus Sicherheitserwägungen niedrig gehalten werden müssen. Daraus ergibt sich die Notwendigkeit einer starken Dampfkühlung und damit einhergehend ein hoher Dampfbedarf. Dies erfordert die Nutzung eines elektrischen Dampferzeugers.

Da die angestrebte Verbrennungseffizienz von 100 % im Rahmen der Brennkammerentwicklung erst erreicht werden muss, sind unverbrannte Reaktanten im Dampf zu erwarten. Aus diesem Grund sollen Verbrennungsversuche zunächst offen, d.h. atmosphärisch durchgeführt werden, bevor sie in einem geschlossenen Kreislauf mit Gegendruck stattfinden. Dafür wird ein Versuchsstand ausgelegt, welcher anschließend durch geringe konstruktive Maßnahmen in das aufzubauende Mikrokraftwerk integriert werden kann. Die Modellierung des Prozesses im Versuchsstand zur Komponentenauswahl wurde mit der Prozesssimulationssoftware Aspen Hysys durchgeführt. Parallel dazu erfolgte auch die Betrachtung möglicher Kraftwerksprozesse. Das Projekt befindet sich aktuell in der Beschaffungsphase für die Komponenten sowie für die Sensorik der Mess- und Regelungstechnik.

In der nachfolgenden Ausführung wird das Ergebnis des iterativen Auslegungsprozesses und die finale Version des Mikrokraftwerks dargestellt.

II. AUSLEGUNG DES MIKROKRAFTWERKS

Grundsätzlich muss beim Betrieb des Demonstrators gewährleistet sein, dass Rückstände von Reaktanten komplett aus dem Kreislauf entfernt werden, da während der Entwicklung der Brennkammer eine vollständige Reaktion nicht in allen Betriebspunkten sichergestellt werden kann. Daher wird eine Prozessführung gewählt, bei welcher der gesamte Dampf kondensiert wird, so dass verbleibende Gase wie H_2 und O_2 entfernt werden können. Dies ermöglich auch eine bessere Bewertung der Brennkammer.

Der den weiteren Betrachtungen zugrunde liegende Prozess ist in ABBILDUNG 1 dargestellt und wird im Folgenden diskutiert.

Zur besseren Verständlichkeit sollen zunächst die verwendeten Bezeichnungen für den Dampfmassenstrom an den jeweiligen Stationen erläutert werden. Die Begriffe sind zur Verdeutlichung auch in ABBILDUNG 1 aufgeführt.

- BK-Dampf: wird durch die Brennkammer geführt und beeinflusst die Reaktionskinetik. Erreicht die höchste Temperatur im Prozess.
- Kühldampf: zur Kühlung der Brennkammer, wird am Austritt mit dem BK-Dampf vermischt.
- Bypassdampf: wird um die Brennkammer geführt und zur Senkung der Prozessdampftemperatur zugemischt.
- Frischdampf: Dampfmenge aus der BK-Dampf, Kühldampf und Bypassdampf gespeist werden. Entspricht der Masse des zu verdampfenden Kondensats.
- Prozessdampf: Dampf aus Verbrennung und Zumischung.

In der Brennkammer (A) wird Wasserstoff und Sauerstoff in Dampf (BK-Dampf) verbrannt. Das Massenverhältnis zwischen BK-Dampf am Eingang der Brennkammer und den Reaktanten wird als Verdünnungsverhältnis oder Dilution Ratio *DR* bezeichnet. Dieser Parameter bestimmt die adiabate Flammentemperatur in der Brennkammer. Anschließend wird am Austritt der Kühldampf beigemischt, der zum Schutz der Brennkammerwand eingesetzt wird (Zustand 2). Nach dem Zumischen des Bypassdampfes (Zustand 3) ergibt sich das globale Verdünnungsverhältnis

$$DR_G = \frac{m_{Frischdampf}}{m_{Reaktanten}} \quad (1)$$

über welches die Temperatur des Prozessdampfes berechnet werden kann.

A. Design des Prototyps

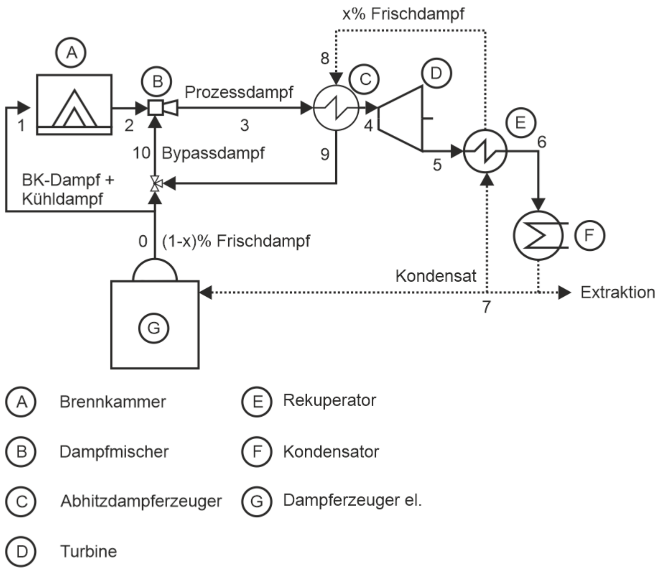


ABBILDUNG 1: DESIGN DES MIKROKRAFTWERKS.

ABBILDUNG 1 zeigt das Modell des Mikrokraftwerks, wie es unter technischen und wirtschaftlichen Bedingungen realisierbar ist. Am Austritt der BK (Zustand 2) dient ein Dampfmischer zur Anpassung der Prozessdampftemperatur (Zustand 3). Stromab folgt der Abhitzedampferzeuger zur Verdampfung des Kondensats bei gleichzeitiger Kühlung des Prozessdampfes auf die TIT (Zustand 4). Nach Expansion in der Turbine (Zustand 5), wird der Dampf durch den Rekuperator (E) geführt. Anschließend wird kondensiert (F) und der Massenanteil der Verbrennungsprodukte extrahiert (Zustand 7). Das restliche Kondensat wird elektrisch (Zustand 0) und durch den Abhitzedampferzeuger (Zustand 8) verdampft.

In den Simulationen für große Kraftwerke im industriellen Maßstab wird mit einer TIT von 1700 °C bei 70 bar (2) gerechnet. Diese Temperaturen lassen sich nur durch eine intensive Turbinenkühlung erreichen.

Mit den hier vorgegebenen niedrigen Turbineneintrittstemperaturen (Zustand 4, 400 °C) liegt der mit dem Demonstrator erzielbare Wirkungsgrad bei etwa 20-25 % und damit deutlich unter den eingangs angegebenen Werten für Kraftwerksprozesse von etwa 70 %. Bei dem vorgesehenen höchsten Prozessdruck von 3 bar, einem Kondensatordruck von 50 mbar und einem isentropen Turbinenwirkungsgrad von 70 % können die in TABELLE I aufgeführten Prozesswirkungsgrade erreicht werden.

TABELLE I: ERREICHBARE THERMISCHE WIRKUNGSGRADE IN ABHÄNGIGKEIT DER TIT, BASIEREND AUF DEM UNTEREM HEIZWERT.

TIT	*Th. Wirkungsgrad*
400 °C	21.25 %
500 °C	23.64 %
600 °C	26.11 %

B. *Autarke Dampfbereitstellung*

Der Zusammenhang zwischen dem globalen Verdünnungsverhältnis DR_G und der Prozessdampftemperatur im Zustand 3 wird in ABBILDUNG 2 (linke Achse) aufgeführt. Mit zunehmendem Verdünnungsverhältnis sinkt die Prozessdampftemperatur, wobei der Kurvenverlauf mit steigendem DR_G asymptotisch wird. Abhängig von der Prozessdampftemperatur kann im Abhitzedampferzeuger (C) ein Teil des Frischdampfes generiert werden (8 → 9).

Dampfturbinen in der Leistungsklasse des Mikrokraftwerks sind auf Grund der Eigenschaften der eingesetzten Werkstoffe auf Turbineneintrittstemperaturen (TIT) von etwa 400 °C limitiert. Deshalb wird der Abhitzedampferzeuger (C) vor die Turbine (D) geschaltet, um die Dampftemperatur abzusenken. Mit der vorgegebenen TIT von 400 °C (Zustand 4), lässt sich mithilfe der Temperatur vor dem Dampferzeuger (Zustand 3) bzw. durch das globale Verdünnungsverhältnis diejenige Frischdampfmenge berechnen, die durch die Wärme des Prozessdampfes quasi autark im Kreislauf generiert werden kann (ABBILDUNG 2 rechte Achse).

Ausgehend von der Dampftemperatur im Zustand 3, d.h. nach der Zumischung des Bypassdampfes (ABBILDUNG 1) wird das entsprechende globale Verdünnungsverhältnis DR_G bestimmt (gestrichelte Linie) und dann für diesen Wert der Anteil des Frischdampfes abgelesen, der damit generiert werden kann. Für die vorliegende Betrachtung liegt der Verdampfungsdruck bei 1 bar; das zu verdampfende Wasser hat die entsprechende Sättigungstemperatur.

Der derzeitige Stand der Technik in Bezug auf die maximale Temperatur für Wärmeübertrager (Zustand 3) liegt bei etwa 800 °C. Damit kann etwa 43 % des Frischdampfes generiert werden (siehe ABBILDUNG 2). Aus Kostengründen wird allerdings häufig eine Maximaltemperatur von 600 °C gewählt, was bedeutet, dass sich nur ca. 20 % des benötigten Dampfes im Prozess autark erzeugen lassen. Für eine vollständig autarke Frischdampferzeugung müsste unter den hier betrachteten Umständen eine Prozessdampftemperatur T_3 von ca. 1200 °C vorliegen. Hitzebeständige Werkstoffe können zwar im Extremfall auf bis zu 1100 °C eingesetzt werden, sind jedoch als Werkstoffe in Dampfprozessen nicht erprobt. Folglich wird für den Aufbau des Demonstrators auf jeden Fall ein zusätzlicher elektrischer Dampferzeuger benötigt, um die notwendige Frischdampfmenge zu generieren.

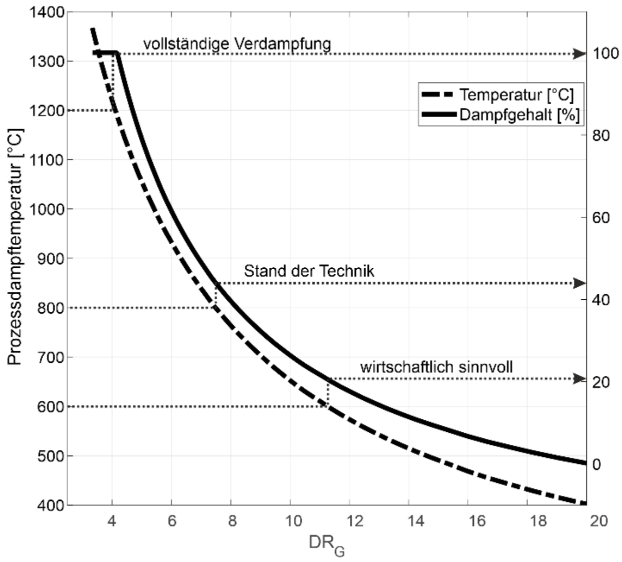


ABBILDUNG 2: ABHÄNGIGKEIT DER GENERIERBAREN FRISCHDAMPFMENGE UND DER PROZESSDAMPFTEMPERATUR VOM GLOBALEN VERDÜNNUNGSVERHÄLTNIS DR_G: GRENZEN DER AUTARKEN DAMPFERZEUGUNG IM MIKROKRAFTWERK.

Derzeit finden erste Gespräche mit dem Southwest Research Institute (SWRI) statt, um die Möglichkeit zur Herstellung von Hochtemperaturwärmeübertragern durch additive Verfahren zu erörtern.

III. ENTWICKLUNG DER BRENNKAMMER

Da bisher kein ausgereiftes Brennkammerkonzept in der Literatur beschrieben ist, werden parallel zur Prozessmodellierung Simulationen zur H2/O2- Verbrennung in Dampf durchgeführt. Basierend darauf wird im nächsten Schritt eine Brennkammer aufgebaut und experimentell untersucht. Die Inbetriebnahme dieses Prüfstands stellt auf Grund der Prozessmedien eine Herausforderung für Mess-, Regelungs- und Sicherheitstechnik dar.

A. *Verbrennungseffizienz*

Für die Modellierung wird eine Verbrennungseffizienz von 100 % für die stöchiometrische Verbrennung von Wasserstoff und Sauerstoff angesetzt. Dieses Ideal wird für die Umsetzung der Edukte im Brennkammer-Prüfstand angestrebt. Bei stöchiometrischem Mischungsverhältnis aus Wasserstoff und Sauerstoff entsteht bei der Verbrennung gemäß der Globalreaktion nur Wasserdampf:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (2)$$

Bei unvollständiger Verbrennung enthält das Abgas und folglich auch der Prozessdampf unverbrannten Wasserstoff und Sauerstoff. Um die Ansammlung von Reaktanten in den Kraftwerkskomponenten zu vermeiden, ist somit die Verbrennungseffizienz nicht nur aus thermodynamischer Sicht ein Schlüsselfaktor für die Entwicklung des Kraftwerks.

B. *Auslegung der Brennkammer*

Die Integration der Brennkammer in den Prozess setzt u.a. kompakte, technisch realisierbare geometrische Abmessungen für das Flammrohr voraus. Alle Komponenten müssen hohe Sicherheitsanforderungen hinsichtlich Druck und Temperatur erfüllen, sowie den Dauerbetrieb der Anlage gewährleisten. Die Auslegung der Brennkammer erfolgt in Kooperation mit dem Institut für Verbrennungstechnik des Deutschen Zentrum für Luft- und Raumfahrt (DLR). Die komplexe Interaktion des Strömungs- und Verbrennungsvorgangs wird zunächst durch Reynolds-Averaged Navier-Stokes (RANS) Simulationen abgebildet. Stationäre Rechnungen ermöglichen hier für verschiedene Brennkammerkonfigurationen numerische Studien zur Verbrennungseffizienz, Wärmefreisetzung, Temperaturverteilung und Abgaszusammensetzung. Anhand der Leistungsabschätzung wurde die Brennkammer dimensioniert und Simulationen zunächst ohne Einbeziehung der Details der Brennergeometrie durchgeführt. Durch Variation des Verdünnungsverhältnisses (DR) bzw. des Dampfmassenstroms lassen sich verschiedene Flammentypen für eine konstante Leistung generieren. In der Literatur (11) werden sowohl für Strahl- als auch für Drallflammen hohe Verbrennungseffizienzen angegeben.

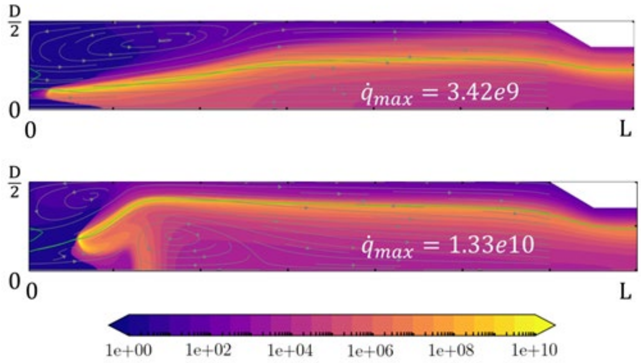


ABBILDUNG 3: VERGLEICH DER WÄRMEFREISETZUNG IN DER STRAHLFLAMME (OBEN) UND IN DER DRALLFLAMME. (QUELLE: DLR)

ABBILDUNG 3 zeigt den Vergleich der Wärmefreisetzung der beiden Flammentypen in einer zylindrischen Brennkammer mit dem Durchmesser D und der Länge L für eine Leistung von 10 kW. Die Drallflamme ist gekennzeichnet durch eine hohe Wärmefreisetzung im ersten Drittel der Brennkammer, da die Verweilzeit der Reaktanten in diesem Bereich im Vergleich zur Strahlflamme erhöht wird, was jedoch auch mit hohen Temperaturen nahe der Brennkammerwand verbunden ist. Ferner zeigt ABBILDUNG 3 deutlich, dass in dieser Konfiguration bei beiden Flammentypen noch signifikante Wärmefreisetzung am Brennkammeraustritt stattfindet - die Verbrennungseffizienz also die angestrebten 100 % bisher nicht erreicht. Die weitere Optimierung ist derzeit Gegenstand der Forschung.

C. Projektierung des Brennkammerprüfstands

1) Sicherheit

Wasserstoff-Sauerstoff-Gemische sind in weiten Konzentrationsgrenzen zündfähig, wobei hohe Verbrennungsgeschwindigkeiten auftreten. Wasserstoffflammen leuchten im ultravioletten Bereich, auf Grund des Fehlens von Kohlenstoffverbindungen ist ihre emittierte Wärmestrahlung eher gering. Prüfstände, bei denen brennbare Gase wie Wasserstoff oder Sauerstoff eingesetzt werden, sind mit entsprechenden Sicherheitseinrichtungen auszustatten und dem Gefahrenpotential durch technische/organisatorische Maßnahmen zu begegnen, um Brand- und Explosionsschutz im Betrieb zu gewährleisten.

2) Mess- und Regelungstechnik

Die Ausstattung des Prüfstandes mit geeigneter Mess- und Regelungstechnik ist eine Herausforderung: die Nutzung etablierter Sensoren und Messtechniken in der Brennkammer z.T. nicht möglich. Eine Schwierigkeit dabei ist das Diffusionsvermögen von Wasserstoff, aber auch die gleichzeitige Anpassung sowohl an die Reaktanten als auch an den Prozessdampf und der Einsatzbereich bei hohen Verbrennungstemperaturen. In-situ Abgasanalyse und Prozessüberwachung benötigen adäquate Probenentnahmesysteme und empfindliche Sensorik mit hoher Ansprechgeschwindigkeit und Messgenauigkeit zur kontinuierlichen Überwachung des Prozesses. Obwohl eine Vielzahl von Sensoren zur Erkennung von Wasserstoff am Markt existieren, bedarf es für die H2/O2- Verbrennung in Dampf angepasste Sensortechnologien, die derzeit noch Gegenstand der aktuellen Forschung und Entwicklung sind.

IV. NÄCHSTE SCHRITTE: BRENNKAMMER-ERPROBUNG UND AUFBAU DES DEMONSTRATORS

Für den Betrieb des Mikro-Kraftwerks muss die Brennkammer zuverlässig und sicher bei höchster Effizienz betrieben werden können. Daher wird der Aufbau des Kraftwerks eng mit dem Fortschritt bzw. der Entwicklung der Brennkammer verzahnt.
Für experimentelle Untersuchungen bei Umgebungsbedingungen wird der am LSM vorhandene Brennkammerversuchsstand verwendet, bevor in der ersten Ausbaustufe ein reiner Brennkammer-Versuchsstand implementiert wird, der aus dem Dampferzeuger, der Brennkammer und einem Gegendruckventil besteht.

Bei dem entworfenen Kraftwerk (ABBILDUNG 1) handelt sich um einen Hybriden, in dem die Frischdampfgenerierung zwischen einem elektrischen und einem thermischen (Rekuperation) Dampferzeuger aufgeteilt ist. Letzterer und die Turbine sind die kostenintensivsten Komponenten des Kraftwerks und werden deshalb während der ersten Brennkammerversuche nicht integriert, um diese vor bauteilschädigenden Verbrennungsrückständen zu schützen. Hierzu wird ein BK-Versuchsstand vorbereitet, welcher bei erfolgreichem Betrieb später zum Kraftwerk umgerüstet werden kann.

A. Vom Versuchsstand zum Kraftwerk

ABBILDUNG 4 zeigt die ersten drei Phasen der Entwicklung:

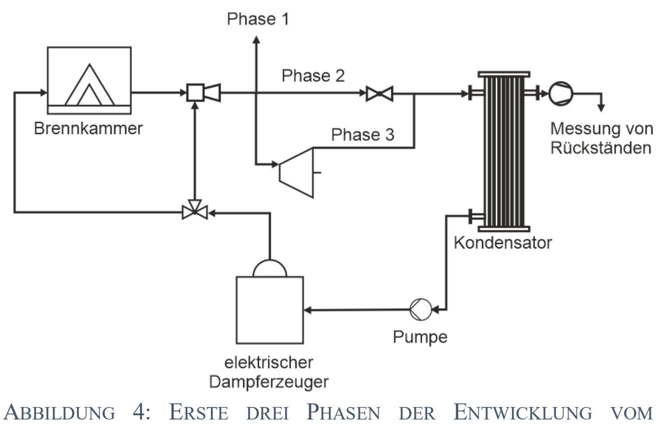


ABBILDUNG 4: ERSTE DREI PHASEN DER ENTWICKLUNG VOM VERSUCHSSTAND ZUM KRAFTWERK.

1) Phase 1: Atmosphärische Verbrennung

Die BK wird offen, d.h. unter atmosphärischen Bedingungen in Betrieb genommen; es werden Verbrennungstemperaturen bestimmt und in-situ Messungen von Verbrennungsrückständen durchgeführt. Ziel ist es, einen sicheren Betrieb und eine effiziente Reaktionsumsetzung zu erreichen. Für die Dampfzufuhr wird ein elektrischer Dampferzeuger beschafft, welcher atmosphärische Brennkammerversuche mit Leistungen von bis zu 450 kW ermöglicht. In dieser Phase wird ebenfalls die Mischung von Kühl- und Bypassdampf für den Prozess optimiert.

2) Phase 2: Schließung des Prozesses

Nach Erreichen einer sicheren und effizienten atmosphärischen Verbrennung wird im geschlossenen Prozess gefahren. Die dadurch entstehende Änderung des Gegendrucks beeinflusst die Strömungsbedingungen und die Verbrennungskinetik.

Der Dampf wird nach einer Drosselung in den Kondensator geführt. Die Drossel ersetzt die Funktion der Turbine und kann bei Versprödung leichter ersetzt werden.

3) Phase 3: Integration der Turbine

Ist eine sichere Verbrennung bei höheren Leistungen und Drücken gewährleistet, kann die Turbine anstelle der Drossel eingesetzt werden. Dies geschieht bereits bei relativ niedrigen BK-Leistungen von ca. 50 kW und einer Prozessdampftemperatur von 400 °C. Zu diesem Zeitpunkt können die ersten Messdaten des Prototyps aufgenommen werden. In dieser Konstellation können BK-Leistungen von bis zu 150 kW bei 3 bar gefahren werden.

B. Finale Version und Ausbau der BK-Leistung

Die finale Version ist in ABBILDUNG 1 dargestellt. Die Integration des Rekuperators (Komponente E) und des Abhitzedampferzeugers (Komponente C) vervollständigt den Prozess. In Bezug auf den Abhitzedampferzeuger besteht jedoch noch technischer Klärungs- und Entwicklungsbedarf aufgrund der hohen thermischen Belastung unter Druck.

Der Frischdampfbedarf steigt invers proportional zur Prozessdampftemperatur. Durch Zuschalten eines hitzebeständigen Abhitzedampferzeugers (Komponente C aus ABBILDUNG 1) kann eine Reduktion des globalen Verdünnungsverhältnisses (DR_G) von 20 auf 8 erreicht werden. Daraus entstehen mehrere Vorteile:

- Eine Reduzierung der Dampfmenge für die Zumischung. Somit werden Kapazitäten für den elektrischen Dampferzeuger frei.
- Ein erhöhter Anteil autarker Dampferzeugung durch Abwärme. Somit sinkt der Anteil der elektrischen Leistung an der Frischdampfgenerierung.
- Freiwerdende Kapazitäten des elektrischen Dampferzeugers ermöglichen eine Erweiterung des Betriebsbereichs der Brennkammer im geschlossenen Prozess. Der Anteil des Bypassdampfes am globalen Verdünnungsverhältnis ist sehr hoch. Wird dieser reduziert können auch höhere Leistungen der Brennkammer getestet werden. Die maximale Leistung des Dampferzeugers beträgt 450 kg/h. Damit können BK-Leistungen von 90 kW bei 400 °C Prozessdampftemperatur erreicht werden. Bei einer Erhöhung auf 800 °C liegt die mögliche BK-Leistung bei 240 kW und bei 440 kW für 1200 °C. Diese höchste realisierbare Temperatur ist abhängig von der thermischen Belastungsgrenze des nachgeschalteten Abhitzedampferzeugers und ist Gegenstand einer Markt- und Literaturstudie.

V. Zusammenfassung

Oxyfuel-Dampfkraftwerke mit Wasserstoffverbrennung können eine schadstofffreie Stromproduktion im MW- oder GW-Bereich mit thermischen Wirkungsgraden höher als 70 % ermöglichen. Um diese Prozesse realitätsnah zu erforschen, wurde im kleinen Maßstab ein Demonstrationskraftwerk ausgelegt, welches im weiteren Projektverlauf aufgebaut wird. Die wirtschaftlichen und technischen Grenzen der Komponenten des Mikrokraftwerks erfordern einen zusätzlichen Dampferzeuger sowie eine schrittweise Umsetzung. Kraftwerk und Brennkammer werden parallel aufgebaut und in Abstimmung zueinander erweitert.

Danksagung

Die Autoren danken Andreas Rauch, Peter Ess und Oliver Lammel vom Institut für Verbrennungstechnik des DLR in Stuttgart für die zur Verfügung gestellte ABBILDUNG 3 und für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt H_2 Oxyfuel].

Literatur

[1] Wojkowsky H, Schnurnberger W, Sternfeld HJ, Peschka W. Hydrogen as an Energy Vector // Stromerzeugung aus Wasserstoff: Proceedings of the International Seminar, held in Brussels, 12-14 February 1980. Dordrecht: Springer Netherlands; 1980.

[2] Funatsu T, Fukuda M, Dohzono Y. Start Up Analysis of a H2-O2 Fired Gas Turbine Cycle. In: ASME 1997 International Gas Turbine and Aeroengine Congress and Exhibition: June 2-5, 1997, Orlando, Florida, USA. New York, N.Y.: ASME; 1997.

[3] Fukuda M, Dozono Y. Double Reheat Rankine Cycle for Hydrogen-Combustion, Turbine Power Plants. Journal of Propulsion and Power 2000; 16(4):562–7.

[4] Sanz W, Braun M, Jericha H, Platzer MF. Adapting the zero-emission Graz Cycle for hydrogen combustion and investigation of its part load behavior. International Journal of Hydrogen Energy 2018; 43(11):5737–46.

[5] Sugishita H, Mori H, Uematsu K. A Study of Advanced Hydrogen/Oxygen Combustion Turbines. In: Hydrogen Power: Theoretical and Engineering Solutions: Proceedings of the Hypothesis II Symposium held in Grimstad, Norway, 18-22 August 1997. Dordrecht: Springer; 1998. p. 511–6.

[6] DIRECT THERMAL DECOMPOSITION OF WATER. In: Ohta T, editor. Solar-hydrogen energy systems: An authoritative review of water-splitting systems by solar beam and solar heat ; hydrogen production, storage and utilisation. 1. ed. Oxford: Pergamon Press; 1979. p. 59–79.

[7] Haidn O, Davidenko D, Gökalp I. Clean Smart Grid: Primary Frequency Control Applying H2/O2 Rocket Combustor Technology 2010.

[8] Malyshenko SP, Prigozhin VI, Savich AR, Schastlivtsev AI, Il'ichev VA, Nazarova OV. Effectiveness of steam generation in oxyhydrogen steam generators of the megawatt power class. High Temp 2012; 50(6):765–73.

[9] Hashimoto T. Hydrogen combustion characteristics in a model burner with a coaxial injector. International Journal of Hydrogen Energy 1998; 23(8):713–20. Available from: URL: https://www.sciencedirect.com/science/article/pii/S0360319997000761.

[10] STERNFELD H, HEINRICH P. A demonstration plant for the hydrogen/oxygen spinning reserve. International Journal of Hydrogen Energy 1989; 14(10):703–16.

[11] Tanneberger T, Schimek S, Kossatz M, Paschereit CO, Stathopoulos P. Development of a swirl-stabilized H2/O2 combustion system under humidified conditions; 2017.

MaST: Scale-Bridging Exploration of Transcritical Fluid Systems

Philipp Neumann*, Amartya Das Sharma, Louis Viot
Helmut-Schmidt-Universität/Universität der Bundeswehr Hamburg
Hamburg, Germany
*philipp.neumann@hsu-hh.de

Theresa Trummler, Alexander Doehring, Min Son, Tobias Sander, Michael Pfitzner, Lars Zigan, Markus Klein
Universität der Bundeswehr München
Neubiberg, Germany

Isabel Nitzke, Simon Homes, Jadran Vrabec
Technische Universität Berlin
Berlin, Germany

Fabio Gratl, Samuel Newcome, Hans-Joachim Bungartz
Technische Universität München
Garching, Germany

Rolf Stierle, Joachim Gross
Universität Stuttgart
Stuttgart, Germany

Axel Auweter, Nico Tippmann
Megware Computer Vertrieb & Service GmbH
Chemnitz, Germany

***Abstract* – Understanding the behavior of multi-component flow systems is a challenging task. This is especially true for mixtures in the transcritical regime, i.e. mixtures under very high pressure but at relatively low temperature, such as fuel injection processes in rocket chambers. The analysis of the underlying flow processes, e.g. droplet and bubble formation, requires detailed multiscale considerations, ranging from molecular properties to large-scale continuum flow field simulation and analysis. In our dtec.bw project "MaST: Macro/Micro-simulation of Phase Decomposition in the Transcritical Regime", we investigate such systems in a multi-disciplinary consortium. Various simulation techniques, including molecular dynamics simulation (MD), classical density functional theory (DFT), computational fluid dynamics (CFD) and scale-bridging molecular-continuum approaches, as well as experimental studies are developed, evaluated, and—where possible—compared for relevant flow scenarios. In this contribution, we report on first case studies, such as injection and multi-phase molecular simulation studies, and on the development of molecular-continuum simulation software for multi-phase and multi-component systems. We further discuss technological requirements for current and anticipated analyses in terms of both experimental set ups, which necessitate the establishment of a high-pressure chamber, and simulation studies, which, due to their high computational intensity, rely on high performance computing approaches.**

Keyword – Computational fluid dynamics, molecular dynamics, density functional theory, injection, high performance computing

NOMENCLATURE

CFD	Computational fluid dynamics
DFT	Density functional theory
fps	Frames per second
MD	Molecular dynamics

I. INTRODUCTION

Injection processes play an essential role in a variety of application fields, such as process, automotive or aerospace engineering. One prominent example is given by the high-pressure injection of fuel into combustion chambers, as used in cars or rocket engines. The underlying process relies on one fluid streaming under extreme pressure conditions into the other, cf. FIGURE 1. Injection processes for such multi-component systems have already been explored for various operating conditions, i.e. various configurations of fluid densities, pressures and temperatures, for different kinds of components. However, the so-called transcritical regime, which is characterized by very high pressures but rather low temperatures, is still not well understood. The transcritical regime is common in the mentioned fuel injection processes. Its investigation is particularly challenging, since the derivation of macroscopic properties such as surface tension, which are required in thermodynamic analyses and CFD simulations, can only be evaluated through fine-scale computations, such as computationally intensive molecular dynamics simulations.

Therefore, the dtec.bw project "MaST: Macro/Micro-simulation of phase decomposition in the transcritical regime" strives to explore these complex flow systems by a highly interdisciplinary approach: experts from thermodynamics, process engineering, fluid dynamics, scientific and high performance computing have teamed up to explore the multi-component systems over a wide range of scales. For this purpose, numerical simulations and their high performance implementations, that are executable on supercomputers due to the simulations' inherently high computational demands, are developed and put into relation with each other to enable a length and time scale-bridging view on the matter, complemented by high-pressure experiments.

In the following, we outline the project developments achieved so far. We explain the injection processes, respective computational fluid dynamics (CFD)- and experiment-based

https://doi.org/10.24405/14537

investigations and our collaborative approach in Section II. At the other end of the scale spectrum, molecular dynamics (MD) simulations are developed and used for investigation of vapor-liquid systems, which are detailed in Section III. Sections IV and V focus on classical density functional theory (DFT) and molecular-continuum simulation methods, which operate on scales between the fine-scale molecular regime and the coarse-scale CFD view. Section VI closes the discussion with a short summary and outlook to future project activities.

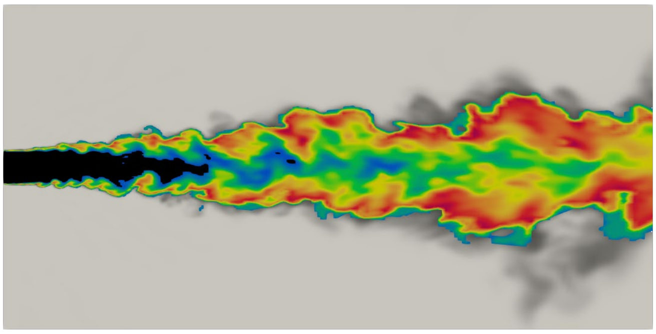


FIGURE 1: TRANSCRITICAL INJECTION OF CYCLO-PENTANE (TEMPERATURE 293 K) INTO NITROGEN (563 K) WITH PHASE SEPARATION DUE TO MULTICOMPONENT MIXING [1]. THE VOLUME FRACTION OF VAPOR IN THE MIXING ZONE IS VISUALIZED BY THE RAINBOW COLOR MAP. THE GRAY SCALE CORRESPONDS TO THE TEMPERATURE.

II. A GLIMPSE INTO THE INVESTIGATION OF INJECTION PROCESSES: AN INTERIDISCIPLINARY EFFORT

A. *Computational Fluid Dynamics for Injection Processes*

At the Institute of Applied Mathematics and Scientific Computing at the Universität der Bundeswehr München, numerical flow simulations are conducted in this project to investigate turbulent mixing and two-phase phenomena in liquid fuel injection and in shear layers. For this purpose, an extended version of the open-source flow solver *OpenFOAM* is used, containing a thermodynamic model that accounts for real gas thermodynamics and phase transition effects. The mixture of two fluids may have a higher critical point than the respective pure substance, resulting in a transition to a subcritical mixture and phase separation effects due to multicomponent mixing. Complex thermodynamic models are required to represent and capture these physical phenomena. FIGURE 1 shows a transcritical injection with phase separation due to multicomponent mixing. The two-phase region in the mixing zone is visualized by the rainbow color map.

B. *Collaborations*

These considerations, that are made at the continuum scale (i.e., in the micro-sized, close-to-visible regime), require close interactions among the entire consortium, that is coordinated by Helmut-Schmidt-Universität Hamburg: reference MD data as well as detailed and accurate MD data for vapor-liquid equilibrium of selected fluid systems have been shared and discussed among the group at the Universität der Bundeswehr München and the group at TU Berlin to ensure consistency of the thermodynamic models at continuum scale [1] with actual molecular behavior. One essential building block consists in a precise formulation and use of equations of state for the underlying fluids. The latter has been subject to close collaboration of Universität der Bundeswehr München with the thermodynamics group at University of Stuttgart, who evaluate the classical DFT against MD simulations. To make respective MD simulations computationally feasible, the group at Technische Universität München collaborates with TU Berlin to improve the computational efficiency of the MD simulation software *ls1 mardyn* and to enable the respective large-scale simulations on supercomputers. This effort is complemented by interactions with the company MEGWARE Computer Vertrieb & Service GmbH to establish an optimal benchmarking platform for simulation software. This is to guarantee a robust performance optimization process, i.e. ensuring a continuous improvement in runtime, over and beyond the project period. To narrow the gap between continuum and molecular investigations, the group at Helmut-Schmidt-Universität Hamburg works on molecular-continuum simulation approaches which incorporate both CFD and MD simulations in a holistic approach. The group interacts with the CFD and MD experts at Universität der Bundeswehr München and TU Berlin and, for the sake of computational efficiency, with the group at Technische Universität München.

While most work in MaST focuses on the application and development of novel simulation techniques, experiments are necessary to validate the simulation results. For this purpose, a special high-pressure chamber is under procurement and installation at the Universität der Bundeswehr München, Institute of Thermodynamics. Selected configurations and operating points have been planned by the CFD and the experimentalist group, with FIGURE 1 illustrating one of these.

C. *Preliminary Spray Experiments with Various Optical Techniques*

Spray experiments were conducted using three different optical diagnostic techniques; the focused shadowgraphy, Mie scattering measurement and high-speed infrared radiation (IR) imaging. The goal of the experiments is a preliminary test for the future work to provide validation data for the simulation groups for CFD and MD simulation, which can model the phase separation of the spray at the transcritical condition.

An optically accessible chamber [2] with quartz and sapphire windows was used to simulate high-pressure and temperature conditions relevant to IC engine and rocket injection as shown in FIGURE 2. Surrogate fuels such as ethanol and cyclo-pentane were injected into the heated nitrogen ambience. A high-pressure gasoline injector with a single injection hole was installed at the bottom of the chamber and the spray was injected in the opposite direction of the ambient nitrogen flow. A Photron Fastcam SA-Z camera with 40,000 fps was used for the shadowgraphy and the Mie scattering measurements. A Telops FAST M2k camera with 4,000 fps and a sapphire window at the imaging side were used for the IR imaging. A single green LED was utilized as the parallel light source for the shadowgraphy, and three perpendicularly arranged white LED flash lamps were applied for the Mie scattering technique. The experiments were conducted at the high-pressure (up to 55 bar for cyclo-pentane and 75 bar for ethanol) and high-temperature (up to 563 K for cyclo-pentane and 768 K for ethanol) chamber conditions.

Since the spray images were captured by the high-speed camera, the spray penetration and evaporation can be analyzed

[1] HTTPS://WWW.UNIBW.DE/NUMERIK-EN

frame by frame as shown in FIGURE 3. The penetration distance and the spray angle can be quantitatively measured from the images, and the instant jet speed can also be calculated. These databases will be used as the validation data for numerical simulations. Spray images from the three different optical techniques can be compared as shown in FIGURE 4; the shadow image shows the jet flow regardless of the phase (darker regions correspond to higher density, i.e. liquid fuel), the Mie image presents the existence of the liquid phase, and the IR image contains the information of

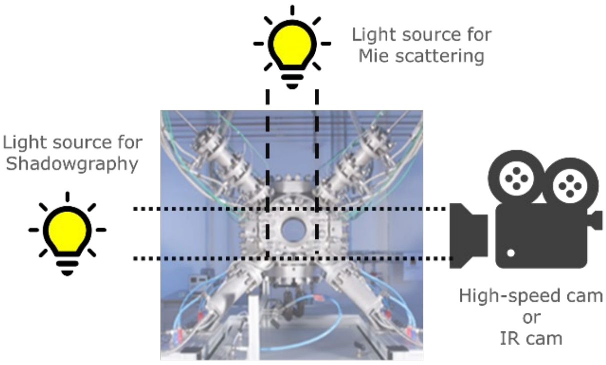


FIGURE 2: EXPERIMENTAL CHAMBER AND OPTICAL SETUP.

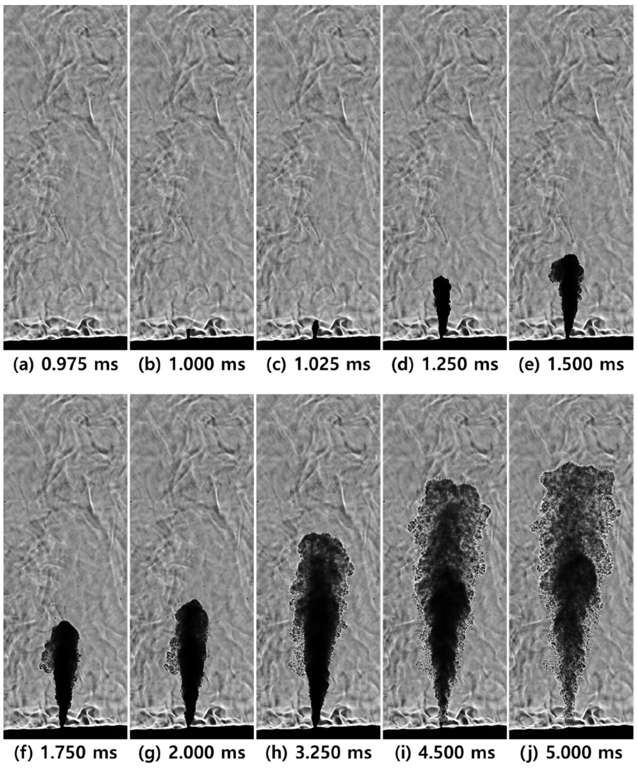


FIGURE 3: HIGH-SPEED SHADOW IMAGES OF THE FUEL JET.

concentration and temperature changes. Combining different methods can provide insight into how the phase change occurs at various ambient conditions. Based on this study, quantitative analysis methods will be developed and a database will be provided as validation data.

III. MOLECULAR DYNAMICS SIMULATION FOR VAPOR-LIQUID SYSTEMS

To elucidate the behavior of vapor-liquid systems in the transcritical regime, atomistic MD simulations are carried out in this subproject. The goal is to directly sample structure and dynamics of the interacting phases during injection processes on the basis of molecular force field models. On the one hand, due to the extreme resolution in time and space, MD is limited to small, yet representative sections of these processes, see FIGURE 5. On the other hand, it is well-suited to yield the full suite of thermophysical properties that are required for models on coarser scales, such as CFD.

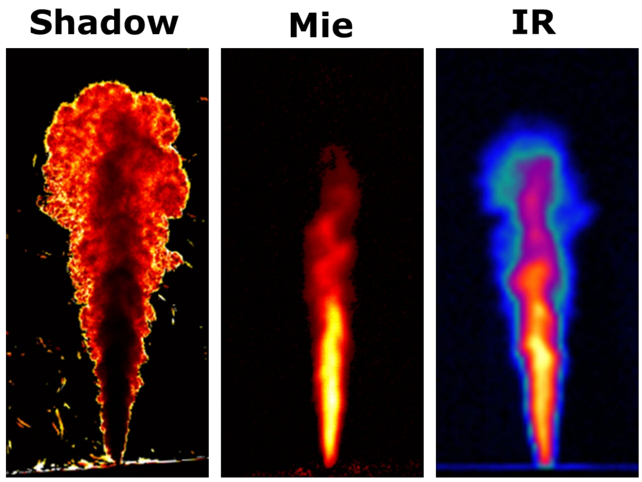


FIGURE 4: COMPARISON OF THREE DIAGNOSTIC METHODS.

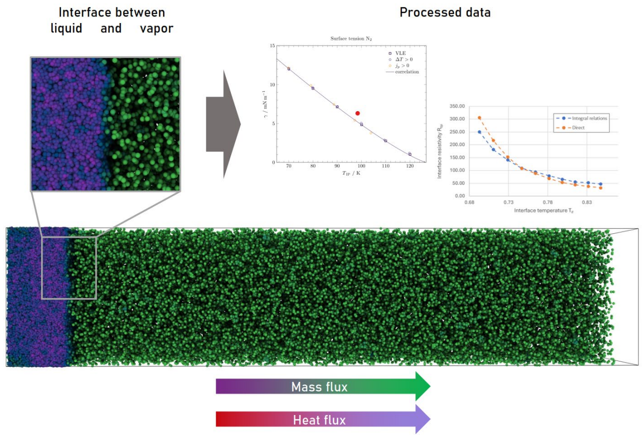


FIGURE 5: SNAPSHOT OF MD SIMULATION WITH MAGNIFIED VIEW ON INTERFACE. PARTICLES BELONGING TO THE LIQUID AND VAPOR ARE COLORED IN VIOLET AND GREEN, RESPECTIVELY.

One topic that was dealt with in the first phase of MaST was the question whether the surface tension under equilibrium conditions is the same as under strong non-equilibrium conditions. While prior work [3] focused on Lennard-Jones model fluids, the objective of the present work was the extension to more complex fluids, whose molecules need to be resolved by several interaction sites or which exhibit a significant polarity. Relying on a reverse non-equilibrium MD method [4], it was demonstrated that neither a large temperature gradient of up to 10^9 K/m, nor a large mass flux density of up to 350 kg/m^{2}s have a significant impact, such that the surface tension depends solely on the local temperature at the interface.

Further work in MaST focused on a first-order phase transition phenomenon, i.e. the evaporation of a liquid. This process occurs in combustion chambers under the influence of strong non-equilibrium conditions, which are particularly suitable for MD simulations. A series of MD simulations considering up to 10^6 particles was utilized to investigate evaporation processes and derive the interface resistivities [5]. Applying a dedicated method [6] to keep the simulation scenario stationary allowed for better statistics and sampling of high-quality data. Varying the imposed parameters, like the bulk liquid temperature or the hydrodynamic velocity in the far field of the vapor, allows for the investigation of their influence on the most relevant quantities, i.e., heat and mass fluxes as well as interface resistivities. For evaporation into vacuum, the fluxes are found to be dependent only on the local temperature at the interface [7].

IV. Density Functional Theory for Mixtures

Classical DFT in conjunction with, e.g., the PC-SAFT equation of state [8, 9, 10, 11], does not only provide physical properties of the vapor and liquid bulk phases of multi-component mixtures (vapor-liquid equilibria, densities, speed of sound, viscosities, thermal conductivities, diffusion coefficients, etc.), but also interfacial properties, i.e. surface tension. To support the development of physical-based interface models for CFD-based simulations, partners from University of Stuttgart work together with colleagues from TU Berlin to predict surface tension and tangential pressures over vapor-liquid interfaces. Classical DFT extends equations of state to inhomogeneous situations. In contrast to equations of state, DFT takes the surroundings (the density profile) into account and is therefore able to describe inhomogeneous fluids at the molecular level, for instance vapor-liquid interfaces or adsorbed molecules on solid surfaces.

Figure 6 exemplarily compares density and tangential pressure profiles for a binary oxygen/cyclohexane mixture from classical DFT with molecular dynamics results for a slab geometry. While the density profiles agree well (small deviations in the bulk phase are due to deviations in the liquid-vapor equilibrium), the tangential pressure profile is slightly offset, which requires further investigation in the future. Surface tensions are determined by integrating the tangential pressure profiles as in Figure 6, so that differences in surface tension can be attributed to differences in these profiles.

V. High Performance Computing for Molecular Dynamics and Molecular-Continuum Simulations

Due to the very limited temporal and spatial scales, that MD simulations can resolve, boosting their computational performance on supercomputers is of utmost importance to the project MaST.

A. *Boosting Performance of Molecular Dynamics: Auto-tuning for multi-site molecule representations*

Partners at Technische Universität München work on the optimization and parallelization of the software *ls1 mardyn*, which is used by the process engineering group from TU Berlin and which achieves high performance on state-of-the-art supercomputers [12]. This includes the particle simulation library *AutoPas*, which is used by *ls1 mardyn* and provides a black-box interface for the costly pairwise force calculation required at each time step in a MD simulation [13]. *AutoPas* selects from a large collection of algorithms the fastest way to calculate the forces acting on each molecule (auto-tuning). Such algorithms include particle containers, such as Linked Cells and Verlet lists, as well as symmetry optimizations (e.g., force balances according to Newton's third law (Newton3)), shared-memory parallel schemes, and vectorization to optimally leverage the entire CPU.

The MD simulation test bed *md-flexible*, used for the experimentation of *AutoPas*, is being extended from single-

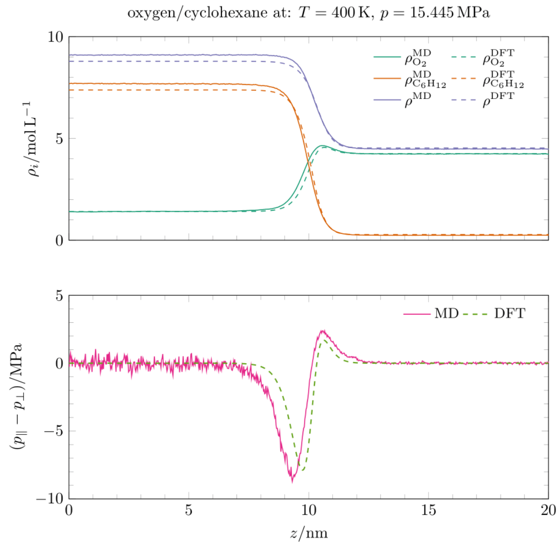


Figure 6: (Partial) density profiles (top) and difference between tangential and normal pressure, $p_{\parallel}$ and $p_{\perp}$ (bottom), for the vapor-liquid interface of the binary mixture of oxygen with cyclo-hexane from DFT and MD calculations.

site Lennard-Jones simulations to rigid-body multi-site simulations. In these, molecules are represented by a small number of fixed sites around a center-of-mass (CoM). The force acting between two molecules is thus the sum of the forces acting between the sites of the molecules, and so, large molecules require quadratically more computational time than small molecules. As *AutoPas* has only been used for particle simulations with uniform pairwise computational costs, MD simulations of molecules with different numbers of sites present a new, unique insight into the use of auto-tuning.

To demonstrate this, the runtime for the force calculation for a scenario with 27,000 molecules with varying numbers of sites was compared for all the algorithms available within *AutoPas*. In Figure 7, we see a comparison of the schemes

- lc_sliced_c02 (linked cells, slicing-based shared-memory parallelization), array-of-structures data structure, no Newton3 optimization, and
- the algorithm lc_c08 (linkd cells, 8-way cell-coloring scheme for shared-memory parallelization), array-of-structures data structure, no Newton3 optimization.

We see that in the 1-site case, lc_sliced_c02 is 21 % faster than lc_c08, but it is 17 % slower in the 5-site case. This demonstrates the advantages of tuning the algorithms used according to the number of sites. In future work, we strive to demonstrate this in full *ls1 mardyn*-based simulations. As part of this, input from partners of TU Berlin has resulted in realistic scenarios to experiment with, so that development of *AutoPas* in this direction can be guided by real world test cases.

The development of high performance software for supercomputers heavily relies on reproducibility of performance metrics such as floating point operations per second or, in the case of MD, molecule updates per second.

The research groups of Technische Universität München and Helmut-Schmidt-Universität Hamburg have teamed up with MEGWARE to leverage a prototype for continuous benchmarking for MaST-related MD simulation developments. One of the next steps in this regard is the deployment of the benchmarking toolkit to the new supercomputer HSUper, which is hosted at Helmut-Schmidt-Universität and which has been extended by even more computational resources to enable the planned large-scale MD simulations.

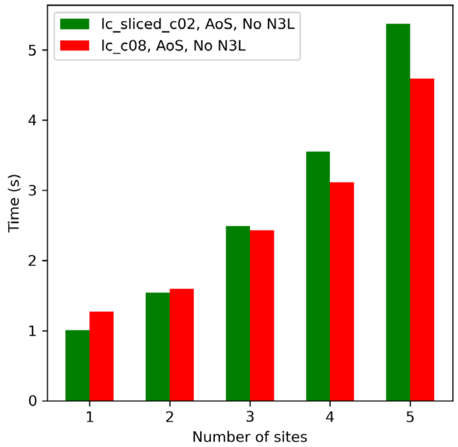


FIGURE 7: COMPARISON OF TWO ALGORITHMS FOR A RANGE OF NUMBERS OF SITES. FOR DETAILS ON THE SPECIFICS OF THESE ALGORITHMS, REFER TO GRATL ET AL. [13].

B. *Boosting Algorithmic Performance by a Multiscale Approach: Towards Molecular-continuum Simulations for Multiphase Systems*

When experimenting on supercomputers with highly optimized MD simulations, one inevitably runs into certain performance limits which are impossible to surpass. Considering very large domains with few rather small-sized regions requiring scrutiny, full sized MD simulations require big computational efforts and appear to be wasteful in terms of their use of HPC resources. Hence the team at Helmut-Schmidt-Universität Hamburg are developing and utilizing the macro-micro coupling tool *MaMiCo* [14], which couples concurrent CFD and MD simulations over large domains, allowing the use of specific solvers for specific regions. Having large CFD volumes in areas of uniform flow, with smaller MD regions only in areas of interest, the aim is to achieve high performance without compromising on the granularity or the quality of the results. Currently, the team at Helmut-Schmidt-Universität collaborate with partners from Technische Universität München and TU Berlin on coupling the solver stack of *ls1 mardyn*/*AutoPas*, and the independent coupling tool *preCICE* to *MaMiCo*.

To couple *ls1 mardyn* to *MaMiCo*, the necessary interfaces on the side of *MaMiCo* have been written and tested. *MaMiCo* can reliably couple with a single *ls1 mardyn/AutoPas* instance placed anywhere within a domain, regardless of whether the *ls1 mardyn* instance is running sequentially or parallel with MPI. Besides, *ls1 mardyn* was refactored to allow for single timestep simulation, and to allow external code to control the simulation steps. The remaining functionality was added via *ls1 mardyn's* plugin system, allowing us to inject coupling code at required moments in the simulation loop. The ensemble builds seamlessly with cmake, and is easy to set up and use. A successful simulation result of coupling *ls1 mardyn/AutoPas* and *OpenFOAM* is shown in FIGURE 9, for which the experimental setup can be seen in FIGURE 8.

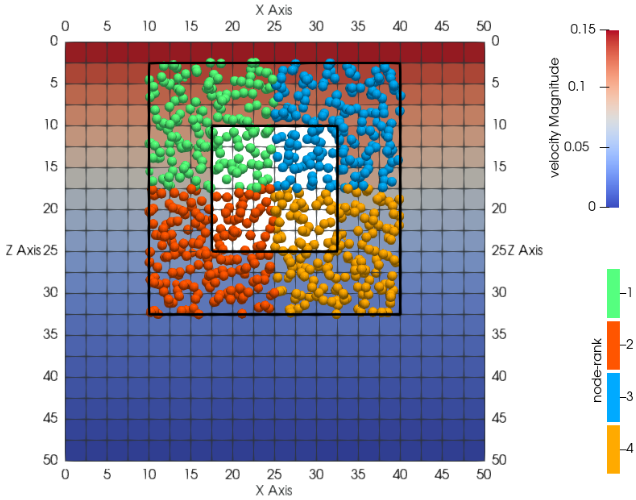


FIGURE 8: EXPERIMENTAL SETUP SHOWING THE CFD DOMAIN AND THE MD DOMAIN. THE AREA BETWEEN THE THICK-LINED BLACK BOXES DENOTES THE OVERLAP REGION IN WHICH CFD AND MD SOLVERS ARE COUPLED. THE GRID SHOWS THE MAMICO COUPLING CELLS.

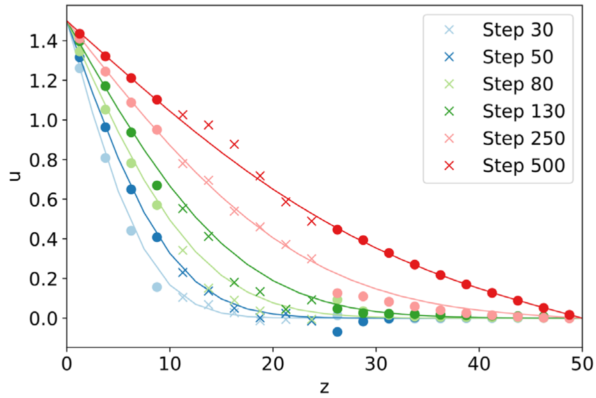


FIGURE 9: VELOCITY PROFILE IN A COUETTE FLOW SIMULATION, COUPLING LS1 MARDYN/AUTOPAS WITH OPENFOAM USING MAMICO. SOLID LINES DENOTE THE ANALYTICAL SOLUTION FOR THE FLUID FLOW VELOCITY IN X-DIRECTION, DOTS REPRESENT DATA EXTRACTED FROM OPENFOAM AND CROSSES REPRESENT DATA FROM LS1/AUTOPAS.

MaMiCo was designed to ease the coupling between MD and CFD solvers. In its core multiple coupling algorithms are present that can be used and reused between the multiple MD and CFD solvers. However, each CFD solver that is to be coupled requires the implementation of a specific *MaMiCo* interface. For more flexibility, we chose to couple the coupling library *preCICE* [15] with *MaMiCo*. Through this *MaMiCo-preCICE* coupling, multiple CFD solvers already adapted to *preCICE*, e.g. *OpenFOAM*, *FEniCS*, etc., shall become usable within *MaMiCo*. Furthermore, this allows us to use the steering methods and (in particular) the implicit coupling schemes of *preCICE*. This will be useful within the context of transcritical multiphase flow with potentially stiff transients which require such schemes. Finally, the interpolation functionalities coming with *preCICE* allow us to use unstructured grids within the CFD solver while using the usual Cartesian grid used for MD simulations.

In the very near future, a multiscale simulation with *ls1 mardyn/AutoPas* and *OpenFOAM* with *preCICE* is to be coupled through *MaMiCo* and executed on the new supercomputer HSUper at Helmut-Schmidt-Universität. This will enable us to compare results at appropriate granularities and verify the robustness of the coupling scheme. This test will then be extended to a variety of hardware, to check for compatibility and ease of use.

VI. Summary and Outlook

We have outlined our current achievements in the dtec.bw project MaST to explore transcritical fluid systems across a wide range of temporal and spatial scales by a variety of simulation methods as well as by experiments. Fruitful collaborations have formed out from the very beginning of the project, which have enabled integral views on research findings, such as a first comparison of MD and DFT data, or information exchange on equations of state for thermodynamically consistent modeling in MD, CFD and molecular-continuum simulations. We look forward to deepening these collaborative investigations and to further following our joint research path in the future.

In order to enhance scientific exchange beyond the MaST research team, a workshop has been conducted mid of September 2022 with several renowned invited speakers. The participation from industrial partners such as MAN and Liebherr will help to stipulate the discussion also towards industrial applications and requirements in the future.

Acknowledgement

The authors thank the group of Professur für Fluidsystemtechnik (FST), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), and Telops Inc. for the support of the experiments. The work described in this contribution has been funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project MaST: Macro/Micro-simulation of Phase Decomposition in the Transcritical Regime].

References

[1] A. Doehring, N. Urban, T. Trummler, M. Pfitzner and M. Klein, "Assessment of a state-of-the-art thermodynamic modelling approach for CFD-simulations under trans- and supercritical conditions," in *4th International Seminar on Non-Ideal Compressible Fluid Dynamics for Propulsion & Power*, City University London, 2022.

[2] S. Riess, L. Weiss, A. Peter, J. Rezaei and M. Wensing, "Air entrainment and mixture distribution in diesel sprays investigated by optical measurement techniqes," *International Journal of Engine Research,* vol. 19, no. 1, pp. 120-133, 2018.

[3] M. Schweizer, H. Öttinger and T. Savin, "Nonequilibrium thermodynamics of an interface," *Physical Review E,* vol. 93, p. 052803, 2016.

[4] F. Müller-Plathe, "A simple nonequilibrium molecular dynamics method for calculating the thermal conductivity," *The Journal of Chemical Physics,* vol. 106, no. 14, p. 6082, 1997.

[5] E. Johannessen and D. Bedeaux, "Integral relations for the heat and mass transfer resistivities of the liquid–vapor interface," *Physica A: Statistical Mechanics and its Applications,* vol. 370, no. 2, pp. 258-274, 2006.

[6] M. Heinen and J. Vrabec, "Evaporation sampled by stationary molecular dynamics simulation," *The Journal of Chemical Physics,* vol. 151, no. 4, p. 044704, 2019.

[7] S. Homes, M. Heinen, J. Vrabec and J. Fischer, "Evaporation driven by conductive heat transport," *Molecular Physics,* vol. 119, no. 15-16, p. e1836410, 2021.

[8] J. Gross and G. Sadowski, "Perturbed-Chain SAFT: An Equation of State Based on a Perturbation Theory for Chain Molecules," *Industrial & Engineering chemistry research,* vol. 40, no. 4, pp. 1244-1260, 2001.

[9] J. Gross, "A density functional theory for vapor-liquid interfaces using the PCP-SAFT equation of state," *The Journal of Chemical Physics,* vol. 131, no. 20, p. 204705, 2009.

[10] E. Sauer and J. Gross, "Classical Density Functional Theory for Liquid–Fluid Interfaces and Confined Systems: A Functional for the Perturbed-Chain Polar Statistical Associating Fluid Theory Equation of State," *Industrial & Engineering Chemistry Research,* vol. 56, no. 14, pp. 4119-4135, 2017.

[11] R. Stierle, E. Sauer, J. Eller, M. Theiss, P. Rehner, P. Ackermann and J. Gross, "Guide to efficient solution of PC-SAFT classical Density Functional Theory in various Coordinate Systems using fast Fourier and similar Transforms," *Fluid Phase Equilibria,* vol. 504, p. 112306, 2020.

[12] S. Seckler, F. Gratl, M. Heinen, J. Vrabec, H.-J. Bungartz and P. Neumann, "AutoPas in ls1 mardyn: Massively Parallel Particle Simulations with Node-Level Auto-Tuning," *Journal of Computational Science,* vol. 50, p. 101296, 2021.

[13] F. Gratl, S. Seckler, H.-J. Bungartz and P. Neumann, "N ways to simulate short-range particle systems: Automated algorithm selection with the node-level library AutoPas," *Computer Physics Communications,* vol. 273, p. 108262, 2022.

[14] P. Neumann, H. Flohr, R. Arora, P. Jarmatz, N. Tchipev and H.-J. Bungartz, "MaMiCo: Software design for parallel molecular-continuum flow simulations," *Computer Physics Communications,* vol. 200, pp. 324-335, 2016.

[15] G. Chourdakis, K. Davis, B. Rodenberg, M. Schulte, F. Simonis, B. Uekermann, G. Abrams, H.-J. Bungartz, L. Yau, I. Desai and K. Eder, "preCICE v2: A sustainable and user-friendly coupling library," *arXiv,* 2021.

Computer-aided and experimental determination of thermophysical properties of gas mixtures containing hydrogen

Robert Hellmann, Ru Wang, Ruben Harten, Karsten Meier*
Institut für Thermodynamik
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Hamburg, Germany
*karsten.meier@hsu-hh.de

Christian Günz, Mathis Manzel, Christof Gaiser*
Physikalisch-Technische Bundesanstalt
Berlin, Germany
*christof.gaiser@ptb.de

Sebastian Schulz, Arne Pietsch, Joachim Zipfel, Philip Jaeger*
Eurotechnica GmbH
Bargteheide, Germany
*philip.jaeger@eurotechnica.de

***Abstract*—In the project H2MIXPROP, highly accurate data for several thermophysical properties of gaseous mixtures containing molecular hydrogen will be obtained by state-of-the-art theoretical approaches and experimental methods. Such data are required for many technical applications in the transition of the energy supply system to renewable energy sources, in which hydrogen is expected to play a prominent role. This contribution describes the used theoretical and experimental methods, safety measures that have to be applied when handling hydrogen in the laboratories, concepts for adapting existing experimental setups for measurements of mixtures containing hydrogen, the design of two new experimental setups for measurements of second virial coefficients of the mixtures, and the current status of the different tasks in the project.**

***Index Terms*—hydrogen, mixture, computer simulation, Burnett method, virial coefficient, viscosity**

I. INTRODUCTION

Thermophysical properties of mixtures containing hydrogen (H_2) are required in the transition of the energy supply system to renewable energy sources in a multitude of technical applications, e.g., in the injection of hydrogen into the natural gas grid or the storage of hydrogen in subsurface caverns. In our project, we predict virial coefficients, viscosity, thermal conductivity, and diffusion coefficients of hydrogen-rich gaseous mixtures on the basis of quantum-chemical *ab initio* calculations of the intermolecular interaction energies. We investigate mixtures of hydrogen with methane (CH_4), nitrogen (N_2), oxygen (O_2), water (H_2O), carbon dioxide (CO_2), hydrogen sulfide (H_2S), ethane (C_2H_6), and propane (C_3H_8). In order to validate the theoretically determined data, experiments for selected mixtures will be carried out with newly developed Burnett instruments at Helmut Schmidt University (HSU) in Hamburg and Physikalisch-Technische Bundesanstalt (PTB) in Berlin, which complement each other with their operating conditions. Moreover, viscosity measurements will be carried out at HSU with two different viscometers. Eurotechnica consults PTB and HSU with regard to laboratory safety for handling of hydrogen and contributes measurements of density, viscosity, phase equilibria, and diffusion coefficients for selected mixtures. For the use in practical applications, the data determined in the project will be represented by correlating equations. Beyond the data for practical applications, the project will yield valuable insights about the possibilities to replace time-consuming, expensive, and possibly even dangerous experiments (e.g., with hydrogen/oxygen mixtures, so-called oxyhydrogen gas) increasingly by computer simulations in the future. Especially at the high temperatures relevant for combustion processes, experiments are virtually impossible, and computer simulations are the only source for the thermophysical properties at these conditions.

II. FIRST-PRINCIPLES DETERMINATION OF THERMOPHYSICAL PROPERTIES

Thermophysical properties of fluids can today be determined very accurately from first principles (i.e., purely from theory). A prerequisite for such calculations are pair potentials, which describe the interaction energy between two molecules as a function of their separation and mutual orientation. For calculations on dense gases and liquids, so-called nonadditive three-body potentials are additionally required. In the group at HSU, interaction energies are computed by means of the supermolecular approach using standard quantum-chemical program packages. Such calculations have to be carried out for a large number of interparticle separations and mutual orientations in order to obtain a complete description of the intermolecular interaction.

https://doi.org/10.24405/14538

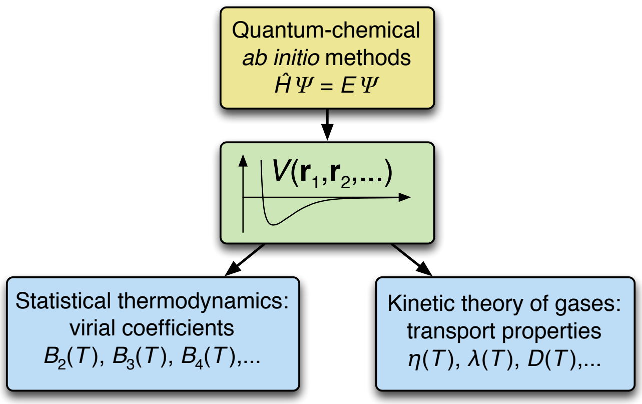


FIGURE 1. ILLUSTRATION OF THE FIRST-PRINCIPLES APPROACH USED AT HSU TO DETERMINE VARIOUS THERMOPHYSICAL PROPERTIES OF GASES AND GAS MIXTURES. THE QUANTITY V IS THE INTERACTION ENERGY BETWEEN TWO OR MORE MOLECULES.

In the next step, suitable mathematical functions are fitted to the calculated interaction energies. Using these potential functions, we can calculate second and higher virial coefficients employing statistical thermodynamics and transport properties in low-density gases and gas mixtures using the kinetic theory of gases. These calculations are performed using unique in-house computer codes.

Whenever possible, the computed property values are compared with experimental data in order to enable a mutual validation of theory and experiment. A great advantage of first-principles approaches over experiments is that a high accuracy can also be achieved at extreme temperatures and for toxic, corrosive, and explosive fluids and fluid mixtures. The experimental effort is often unjustifiably high in these cases.

The described theoretical approach, illustrated as a flow chart in FIGURE 1, is used in this project to determine second virial coefficients, shear viscosities, thermal conductivities, and mutual diffusion coefficients of eight binary systems containing H_2. In addition to mixtures of H_2 with CH_4, C_2H_6, C_3H_8, N_2, and CO_2, for which also extensive experimental work is conducted in this project (see below), mixtures of H_2 with H_2O, H_2S, and O_2 are investigated theoretically. The mixtures with H_2O and H_2S are difficult to handle in experiments due to the corrosive impact of these two gases on the equipment and due to the high toxicity of H_2S. In the case of mixtures of H_2 and O_2 (oxyhydrogen gas), experimental investigations are impossible because this mixture is highly explosive.

Most of the nine pure gases from which the eight selected binary systems are formed were already studied previously, see, e.g., the work of Hellmann on C_2H_6 [1], C_3H_8 [2], and CO_2 [3] or the work of Patkowski et al. [4] and Mehl et al. [5] on pure H_2. A detailed theoretical investigation of the thermophysical properties of pure O_2 is part of the present project.

For six of the eight binary systems and for pure O_2, the quantum-chemical calculations are completed by now. The next work step for these systems, the fit of mathematical functions to the interaction energies, is well underway, so that the calculation of the thermophysical properties will soon begin.

III. LABORATORY SAFETY FOR HANDLING HYDROGEN

Some components of the investigated mixtures, e.g., hydrogen, methane, ethane, or propane, form explosive mixtures when mixed with ambient air. Therefore, special safety measures must be applied when experiments with these mixtures are carried out. Our safety concept for the laboratory is based on the principle of "permanently technically tight systems" according to the Technical Rule for Hazardous Substances TRGS 722 for all experimental setups because this way the laboratory room does not need to be declared as an explosive zone. Permanently technically tight systems form also a basic requirement for conducting highly accurate measurements with gas mixtures, especially for the Burnett method. In order to realize permanently technically tight experimental setups, the gas mixtures must be prevented from leaking from the high pressure zones of the experimental setups into the laboratory room. In particular, hydrogen imposes high requirements on the tightness because of the small size of its molecules. Therefore, the tightness of all connections in the high-pressure valve systems and at the pressure vessels is checked by carrying out leak tests with helium before commissioning. These leak tests are always repeated before an apparatus is filled with a new gas mixture. When an experimental setup is filled with hydrogen or a mixture containing hydrogen, rather hydrogen instead of helium is used as test gas. With the leak tests, it is ensured that leaks are detected and cleared before a new measurement campaign is started.

The pressure vessels for the experimental setups are developed by Eurotechnica based on the European pressure directive and will be inspected and certified by TÜV (notified body as per European pressure directive). Hydrogen causes hydrogen embrittlement in some steels, resulting in a drastic reduction of the elongation at fracture. All parts that are in contact with hydrogen and whose fatigue poses a safety risk must be made of materials compatible with hydrogen. To counteract hydrogen embrittlement, stainless steels with a nickel content above 12 % and a low molybdenum content of 2 % to 3 % must be employed [6].

To maximize safety in the laboratory, several worst-case scenarios were considered and evaluated. Due to the small internal volumes of the experimental setups between 100 ml and 1000 ml and the comparatively high volume of the laboratory room (e.g., 152 m^3 at HSU), even an unnoticed leakage of the entire filling of a setup could be classified as non-critical because the limit of flammability for all pure gases and gas mixtures will not be exceeded. In addition to the safety measures taken, sensors for the detection of hydrogen, methane, ethane, and propane are installed in the room to indicate when concentrations of explosive gases exceed the flammability limits in the laboratory room. When the sensors indicate increased concentrations of the explosive gases, an emergency plan, which describes the required measures, applies.

Other scenarios examined are the failure of the cooling system of the thermostat of the torsional crystal viscometer, the temperature increase of hydrogen caused by the Joule–Thomson effect, when a pure explosive gas or a gas mixture is released to the environment, and the formation of an explosive mixture with ambient air upon discharge of the entire filling of an experimental setup to the environment. When the cooling system of the thermostat of the torsional crystal viscometer during operation at temperatures below ambient fails, the temperature and pressure of the gas mixture in the pressure vessel increase. When this failure occurs at low temperatures between 200 K and 240 K at the highest measured pressures between 80 MPa and 100 MPa, the upper pressure limit of the pressure vessel can be exceeded when the thermostat heats up to ambient temperature. Thus, in this range of temperature and pressure, the measurements must not be carried out by automatic operation, but under surveillance of the operator. The release of hydrogen from any of the experimental setups to the environment results only in a temperature increase of 20 K at maximum. Even at the highest operating temperature of the vibrating-wire viscometer, the spontaneous ignition temperature of hydrogen of 858 K will never be reached. The outlet of all high-pressure systems at HSU is above the roof of the laboratory building. When an entire filling of an experimental setup is discharged to the environment, an explosive mixture within a spherical volume of 2.7 m radius around the outlet can form in the worst case. Therefore, warning signs “No Smoking or Open Fires” will be mounted near the outlet on the roof and at the side wall of the building. Overall, the chosen concept ensures safe operation of the experimental setups with hydrogen and mixtures containing hydrogen in the laboratory room.

IV. Virial Coefficients from the Burnett Method

A. Working Principle of the Burnett Method

The equation of state (EOS) of a gas plays an important role in both academic and industrial applications. The Burnett technique provides a simple experimental method, in which neither the mass nor the volume of gas has to be measured.

The principle of a Burnett apparatus is sketched in Figure 2. Two vessels with volumes V_A and V_B are placed in an isothermal bath. The gas to be measured is filled into volume V_A via the supply valve v_1 at a high pressure p_0. After thermal equilibrium has been established, the EOS of the gas is expressed by

$$p_0 V_\mathrm{A} = Z_0 mRT, \tag{1}$$

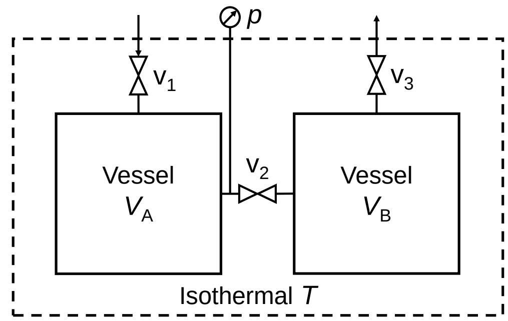


Figure 2. Working principle of a Burnett apparatus.

where Z_0 is the compressibility factor at pressure p_0, m is the mass of the gas, and R is the specific gas constant.

When the expansion valve v_2 is opened, the gas expands into the second vessel. Once thermal equilibrium is established again, the pressure in the system is p_1, and the EOS is expressed by

$$p_1(V_\mathrm{A} + V_\mathrm{B}) = Z_1 mRT, \tag{2}$$

where Z_1 is the compressibility factor at pressure p_1. Dividing (2) by (1) yields

$$\frac{p_1(V_\mathrm{A} + V_\mathrm{B})}{p_0 V_\mathrm{A}} = \frac{Z_1}{Z_0}, \tag{3}$$

in which $(V_\mathrm{A} + V_\mathrm{B})/V_\mathrm{A}$ defines the volume ratio N of the apparatus.

After closing the expansion valve v_2 and evacuating volume V_B, the remaining gas in volume V_A is expanded again. This process is repeated until the absolute pressure reaches the lowest value that can be accurately measured. For the ith expansion, (3) is written as

$$\frac{p_i N}{p_{i-1}} = \frac{Z_i}{Z_{i-1}}. \tag{4}$$

If the expansion is repeated infinitely often, the gas will be diluted to the state of an ideal gas, which corresponds to the compressibility factor $Z_\infty = Z_{\infty-1} = 1$ and $N = p_{\infty-1}/p_\infty$. The relation of the pressure ratio p_{i-1}/p_i to p_i can be represented by a polynomial:

$$\frac{p_{i-1}}{p_i} = a + bp_i + cp_i{}^2 + \dots. \tag{5}$$

Thus, the volume ratio N can be determined by the intercept of this polynomial when p_i is equal to zero after infinitely many expansions.

From (4), we obtain

$$\prod_{i=1}^{n} \frac{p_i}{p_{i-1}} N^n = \prod_{i=1}^{n} \frac{Z_i}{Z_{i-1}}, \tag{6}$$

which can be simplified to

$$\frac{p_n N^n}{p_0} = \frac{Z_n}{Z_0}. \tag{7}$$

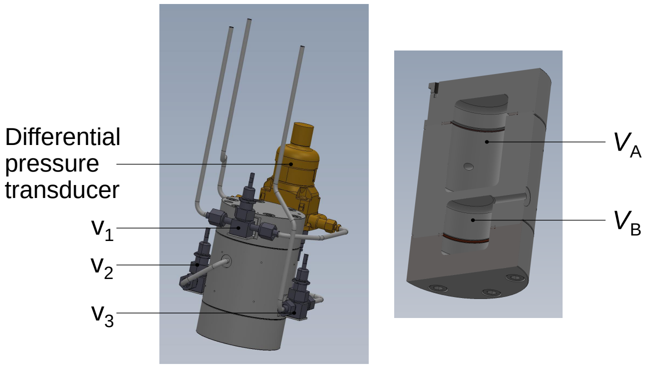


FIGURE 3. DESIGN OF A NEW BURNETT APPARATUS AT HSU. THE LEFT SUBFIGURE SHOWS THE PRESSURE VESSEL WITH THE VALVE SYSTEM AND DIFFERENTIAL PRESSURE TRANSDUCER, AND THE RIGHT SUBFIGURE IS A CROSS SECTION OF THE PRESSURE VESSEL.

Considering $p_n N^n$ as a polynomial in p_n and assuming that n is infinite, so that $Z_\infty = 1$, the intercept of the polynomial at $p_\infty = 0$ is $p_\infty N^\infty$, which by (7) is equal to p_0/Z_0.

Combining this result with (7), the compressibility factor Z_i for each expansion step is obtained as

$$\frac{p_i N^i}{p_\infty N^\infty} = \frac{Z_0 p_i N^i}{p_0} = Z_i. \tag{8}$$

The virial coefficients are obtained by a least-squares fit of the virial expansion

$$Z_i = 1 + b_2(T)p_i^2 + b_3(T)p_i^3 + \dots, \tag{9}$$

where b_i denotes the i-th pressure virial coefficient, to the compressibility factors of the expansion series as a function of pressure. Finally, the pressure virial coefficients b_i are converted to the density virial coefficients B_i of the density expansion

$$Z = 1 + B_2(T)\rho^2 + B_3(T)\rho^3 + \dots \tag{10}$$

by well-known relations.

B. Design of a New Burnett Apparatus at HSU

In the group at HSU, a new improved Burnett apparatus has been designed and is being set up, as shown in FIGURE 3. It is designed for the temperature range from 233 K to 343 K with pressures up to 7 MPa. The two chambers V_A and V_B have a volume ratio of approximately 1.45 and are dug out from both ends of a pressure vessel, which is made of stainless steel 1.4980. This material is an austenitic precipitation-hardened stainless steel, has a high creep resistance, and is compatible with hydrogen in the working range of the apparatus. The three main valves for supply (v_1), expansion (v_2) and discharge (v_3) of the gas are retrofitted with motors, which are controlled and operated automatically by the data acquisition computer. The hydrogen mixture is separated from the absolute pressure transducer by a differential pressure transducer, in which a membrane with gold plating on the hydrogen side acts as a separator. The branch of the valve system with the absolute

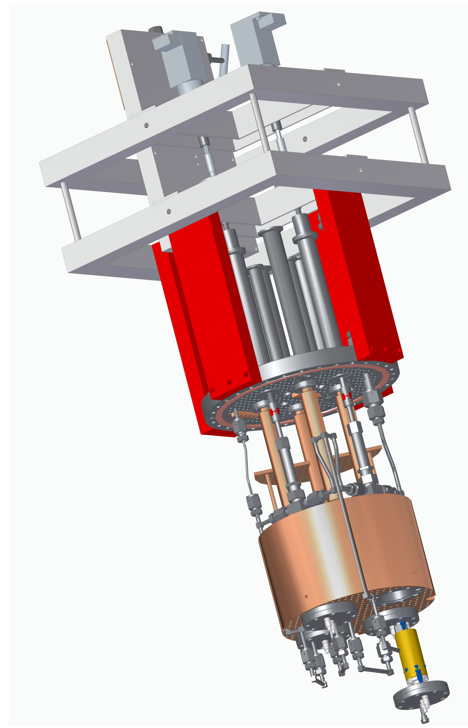


FIGURE 4. DESIGN OF THE NEW COMBINED EXPANSION APPARATUS. CAPACITORS ARE SITUATED IN THE COPPER BLOCK WITH THE EXPANSION VALVES MOUNTED ON TOP. THESE PARTS ARE SURROUNDED BY A VACUUM CHAMBER IMMERSED IN A CONTROLLED WATER BATH. THE PRESSURE SENSORS AS WELL AS THE MOTORS AND THE GEARS FOR THE EXPANSION VALVES ARE OUTSIDE THE WATER BATH.

pressure transducer is filled with nitrogen. The pressure vessel, the three valves v_1, v_2, and v_3 and the differential pressure transducer are thermostated in a circulating liquid bath thermostat with silicone oil as thermostating liquid. The thermostat ensures a temperature stability better than 0.5 mK. Since the uncertainty of the measured virial coefficients is mostly influenced by the uncertainty of the pressure measurement, the absolute pressure transducer is calibrated before each expansion series with a highly accurate gas piston gauge. In order to avoid zero point shifts of the differential pressure transducer during a measurement campaign, the zero point is also calibrated before each expansion series. The temperature is measured by a long-stem standard platinum resistance thermometer calibrated on the ITS-90 in the wall of the pressure vessel with an uncertainty of a few mK by a resistance bridge system.

The design of the pressure vessel, valve system, and pressure measurement system is completed. Technical drawings for the presure vessel and all mechanical parts were issued, and the manufacturing has been started. Moreover, a concept for automation of the calibration of the pressure sensors and measurement of an expansion series was developed, and some components of the data acquisition software have been coded in the graphic programming environment LabVIEW.

C. Implementation of a Burnett Apparatus at PTB

The apparatus designed at PTB is a combination of three different methods. The first and extensively explored method is the so-called Dielectric-Constant Gas Thermometry (DCGT) based on replacing the density in the equation of state of a gas by the dielectric constant. The dielectric constant is determined via the change of the capacitance of a capacitor measured with and without the gas. This method of primary thermometry has already been successfully used to determine combinations of density and dielectric virial coefficients [7], [8]. The drawback of this approach is the impossibility to differentiate between both contributions since capacitance and pressure data is utilized in combination. That is why these experiments are coupled with Burnett and dielectric expansion experiments where pressure and capacitance ratios are defined by repeated expansion of gas from one into another volume as mentioned in Section IV-A. From these ratios, the independent density and dielectric virial coefficients can be determined without the need to assess the absolute particle density. Both methods typically require large experimental setups whose manual operation is time consuming. In the last years at PTB, a compact apparatus was developed that combines both experimental approaches, in which the expansions are fully automated [9], [10]. This apparatus was used for experimental studies on noble gases. Within the framework of the project, a new improved apparatus especially dedicated to measurements of hydrogen/methane mixtures will be built (see FIGURE 4). In contrast to the forerunner, the expansion valves will be situated inside the vacuum chamber, reducing the amount of gas not being thermostated precisely at the designated temperature. Since, for thermal reasons, the motors for the valves are outside the vacuum chamber, the use of appropriate vacuum feedthroughs, torque regulators, and so forth must be included in the design. Furthermore, the new apparatus will have an improved thermal environment of the expansion cells. The materials for the parts in contact with the gas have been proven to be compatible with hydrogen. Beside these large changes, there are other lessons learned from the first apparatus, so that the data evaluation should be more straightforward for the new setup.

V. VIBRATING-WIRE AND TORSIONAL CRYSTAL VISCOMETERS

A. Vibrating-Wire Viscometer

The vibrating-wire viscometer at HSU was originally developed by Seibt [11] at the University of Rostock in the group of Prof. Eckhard Vogel and was applied there to measure the viscosity of gaseous nitrogen, methane, ethane, propane, n-butane, and isobutane [11], [12]. After the retirement of Prof. Vogel, it was transferred to HSU, rebuilt in our laboratory, and used to measure the viscosity of the noble gas neon by Kochan-Eilers [13]. The experimental setup (FIGURE 5) consists of a single-sinker densimeter and three vibrating-wire sensors (FIGURE 6) in a single pressure vessel and enables simultaneous measurements of the density and viscosity of a gas. It covers the temperature range between 293 K to 498 K at pressures up to 30 MPa. The density measurements are characterized by a relative expanded uncertainty (coverage factor $k = 2$) of 0.1 %, except in the low density range, where it is larger, while the relative expanded uncertainty ($k = 2$) in the viscosity is estimated to be 0.25 % to 0.3 %.

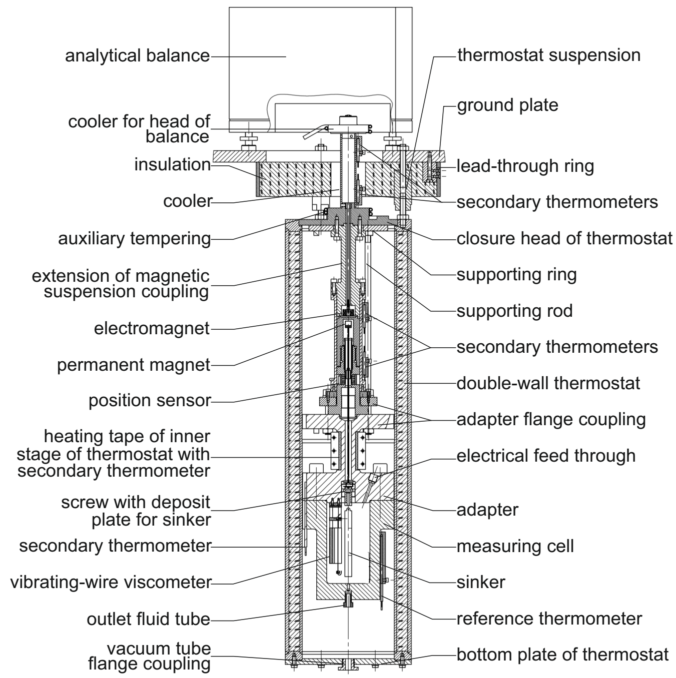


FIGURE 5. CROSS-SECTION OF THE VIBRATING-WIRE VISCOSIMETER USED AT HSU.

FIGURE 6. PHOTO OF A VIBRATING-WIRE SENSOR (WIRE NOT TENSIONED).

A vibrating-wire sensor (FIGURE 6) consists of a Chromel® wire with a diameter of 25 μm, which is clamped at both ends and tensioned between two permanent samarium-cobalt magnets by a lever arm with a weight at its lower end. By applying a sinusoidal alternating voltage along the wire, it is excited to vibrate. After switching off the excitation voltage, the magnetic field between the two magnets induces an alternating current in the freely vibrating wire. By measuring the voltage along the wire as a function of time, the damping of the vibration can be recorded and evaluated. The viscosity η of the gas is determined by the working equation

$$\eta = \frac{2\pi f_{\mathrm{F}} \rho R^2}{\Omega}, \tag{11}$$

where R is the radius of the wire, ρ is the density of the fluid, f_{F} is the resonant frequency of the wire in the gas, Ω is a function of the mechanical properties of the wire, and the resonant frequency and logarithmic decrement of the vibration of the wire in vacuum and in the fluid. The radius of the wire is determined from calibration measurements with helium, while the density of the gas can either be measured with the single-sinker densimeter or calculated with an equation of state if an accurate one is available for the gas. The resonant frequency and logarithmic decrement of the vibration in vacuum and in the fluid are determined from the measured voltage data of the decay of the free vibration.

For measurements of hydrogen and mixtures containing hydrogen, some components of the valve system, a differential pressure transducer, which couples the measured gas with the nitrogen in the pressure measurement system, and the pressure vessel must be replaced by components, in which the parts in contact with hydrogen are made of materials compatible with hydrogen. The differential pressure transducer (Emerson, type 3051) is replaced by a new transducer of the same type, in which the stainless steel membrane, which separates the measured gas from the nitrogen, is gold plated on the side in contact with hydrogen. The gold plating prevents hydrogen from diffusing into and through the membrane. A new pressure vessel made of a copper alloy with high mechanical strength and high thermal conductivity is designed by Eurotechnica. The certification of the pressure vessel by the TÜV requires more thorough proofs than for pressure vessels of conventional materials because copper alloys have not often been applied yet for pressure vessels operated with hydrogen in the temperature and pressure range of the vibrating-wire viscometer.

Additionally, further changes will be introduced to improve the performance of the viscometer. Beside the Chromel wire, a gold-plated tungsten wire with a smooth surface will be tested. Tungsten has a higher density, a higher elastic modulus, and a lower coefficient of thermal expansion than Chromel, and the application of tungsten wires is expected to improve the reproducibility of the measurements. In previous realizations of vibrating-wire viscometers, mostly pure tungsten wires were used, which had a very rough surface [14]. With the gold plating, the surface roughness of tungsten wires is reduced considerably.

With the current setup, the temperature control of the thermostat of the viscometer was sometimes unstable because of heat losses at the top cover of the thermostat. A new temperature-controlled heating coil will be applied near the top cover to decouple the pressure vessel in the thermostat thermally from the laboratory environment. In addition, a stand-alone setup with a single vibrating-wire sensor in a new pressure vessel will be built. The pressure vessel will be thermostatted in a circulating liquid oil bath of a calibration thermostat with a temperature stability of 5 mK (Fluke Calibration 7341). The pressure vessel is also designed by Eurotechnica and made of the stainless steel 1.4980. It is expected that thermal equilibrium in the pressure vessel and gas is attained much faster than in the rather complex combined densimeter viscometer due to the convective heat transfer in the liquid bath thermostat.

Moreover, the operation of the viscometer will be automated. A pressure controller (WIKA, type CPC8000) will be used to control the pressure of the nitrogen in the pressure measurement system branch of the valve system. The manual valves for discharging gas from the high pressure system will be replaced by pneumatic valves, which will be controlled by the data acquisition computer. By using a computer-controlled relay switch system, the data acquisition computer can automatically switch between the three different vibrating-wire sensors.

B. *Torsionally Vibrating Crystal Viscometer*

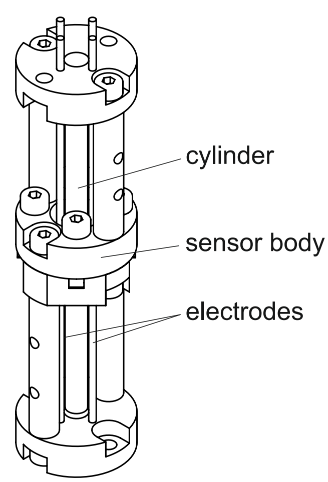


FIGURE 7. THREE-DIMENSIONAL VIEW OF THE SENSOR OF THE TORSIONALLY VIBRATING CRYSTAL VISCOMETER.

The use of piezoelectric cylinders, which vibrate in the fundamental torsional mode, as viscosity sensors was first suggested by Mason [15]. Almost exclusively piezoelectric quartz cylinders with diameters of a few mm and lengths of a few cm have been applied, whose cylinder axis is aligned in parallel with the X axis of the crystallographic lattice coordinate system of quartz. Four separate electrodes with their centers at angles of $\pi/4$ between the Y and Z axes surround the crystal as separate parts in a quadrupole arrangement. When an alternating electric field is applied to the electrodes, the cylinder is excited to torsional vibrations, which are damped by the surrounding fluid. The working equation of the torsionally vibrating crystal viscometer is given by

$$\eta\rho = \left(\frac{m}{S}\right)^2 \pi f_\mathrm{F} \left(\frac{\Delta f_\mathrm{F}}{f_\mathrm{F}} - \frac{\Delta f_0}{f_0}\right)^2, \qquad (12)$$

where m is the mass of the cylinder and S denotes its surface area. The resonant frequency f_F and the bandwidth Δf_F in the fluid and the respective quantities in vacuum f_0 and Δf_0 are determined from measured curves of the conductance and susceptance of the viscosity sensor in the vicinity of the resonant frequency in the frequency domain. The mass of the cylinder is accurately determined by weighing with a mass comparator, while the surface area can in principle be determined from dimensional measurements of the length and of the curved surface of the cylinder. In practise, an effective radius of the cylinder is determined by calibration measurements with a liquid viscosity standard. The density must either be measured separately or calculated with an equation of state.

Junker developed and operated a torsionally vibrating crystal viscometer for measurements of liquids in the temperature range between 240 K and 420 K with pressures up to 100 MPa at HSU [16]. As part of that work, the electric field in the viscosity sensor was analyzed [17], and the deformation of the anisotropic quartz cylinder in the fundamental torsional mode was investigated in detail [18]. Here, the viscometer will be used to measure the viscosity of hydrogen mixtures, especially at temperatures below ambient, where the vibrating-wire viscometer cannot be applied. The pressure vessel will be replaced by a new one made of stainless steel 1.4980 developed by Eurotechnica, while all parts of the valve system (SITEC, 1000 Micro) are made of stainless steel 1.4571 and are compatible with hydrogen. The computer-controlled syringe pump used to set the pressure when measuring liquids will be replaced by an electric pump with a larger swept volume for measurements of gases (SITEC 750.6101-1-sp with hydrogen-compatible materials).

The data acquisition system of the viscometer will be extended by a fast digital oscilloscope card (Spectrum Instruments, type M4i4420-x8) for measurements of the free vibration in the time domain, which reduces the required time for a measurement considerably compared to measurements of complete resonance curves in the frequency domain. This technique was first realized with quantitative results by Hafer and Laesecke [19]. Furthermore, it will be examined if the dimensions of the cylinder can be determined by measurements with an optical technique with sufficient accuracy to realize absolute measurements of the viscosity without the need for calibration. Additionally, the surface roughness of the cylinder will be characterized, and its influence on the results for the viscosity will be examined.

VI. Outlook

In the first phase of the project, the potential energy surfaces for the eight investigated binary mixtures with hydrogen and pure oxygen are developed in the theoretical part of the project. On the experimental side, the Burnett apparatuses at HSU and PTB were drafted, technical drawings for the main subassemblies were prepared, wrought materials, components, and measurement devices were selected and ordered, and manufacturing of the mechanical parts of the setups was started. Moreover, a concept for automation of the Burnett apparatus at HSU was developed and some components of the data acquisition software were written. For the vibrating-wire and torsionally vibrating crystal viscometers at HSU, concepts for their adaption for measurements of hydrogen mixtures and their automation were developed.

In the next phase, the potential energy surfaces will be finalized and applied to calculate the thermophysical properties of the mixtures and pure oxygen. Moreover, the experimental setups at HSU and PTB will be assembled in the laboratories and commissioned. Before the measurements of the hydrogen mixtures, calibration measurements of the new Burnett apparatuses and the vibrating-wire viscometer with helium will be carried out. Subsequently, the Burnett apparatuses will be validated by measurements with argon and nitrogen, for which the second virial coefficients are very accurately known.

Acknowledgment

This work was funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr [Energy and Digitalization].

References

[1] R. Hellmann, “Reference Values for the Second Virial Coefficient and Three Dilute Gas Transport Properties of Ethane from a State-of-the-Art Intermolecular Potential Energy Surface,” J. Chem. Eng. Data **63**, 470–481 (2018).

[2] R. Hellmann, “Intermolecular potential energy surface and thermophysical properties of propane,” J. Chem. Phys. **146**, 114304 (2017).

[3] R. Hellmann, “*Ab initio* potential energy surface for the carbon dioxide molecule pair and thermophysical properties of dilute carbon dioxide gas,” Chem. Phys. Lett. **613**, 133–138 (2014).

[4] K. Patkowski, W. Cencek, P. Jankowski, K. Szalewicz, J. B. Mehl, G. Garberoglio, A. H. Harvey, “Potential energy surface for interactions between two hydrogen molecules,” J. Chem. Phys. **129**, 094304 (2008).

[5] J. B. Mehl, M. L. Huber, A. H. Harvey, “Ab Initio Transport Coefficients of Gaseous Hydrogen,” Int. J. Thermophys. **31**, 740–755 (2010).

[6] G. R. Caskey, “Hydrogen effects in stainless steel,” Du Pont de Nemours (E.I.) and Co., Aiken, SC (United States), Savannah River Lab (1981).

[7] C. Gaiser and B. Fellmuth , “Highly-accurate density-virial-coefficient values for helium, neon, and argon at 0.01°C determined by dielectric-constant gas thermometry,” J. Chem. Phys. **150**, 134303 (2019).

[8] R. Hellmann, C. Gaiser, B. Fellmuth, T. Vasyltsova, and E. Bich, “Thermophysical properties of low-density neon gas from highly accurate first-principles calculations and dielectric-constant gas thermometry measurements,” J. Chem. Phys. **154**, 164304 (2021).

[9] C. Guenz, C. Gaiser, and M. Richter, “Concept of a new technique for the combined determination of dielectric and density virial coefficients,” Meas. Sci. Technol. **28**, 027002 (2017).
[10] C. Guenz “Combined Dielectric-Constant Gas Thermometry and Expansion Experiments - Virial Coefficients of Argon,” Thesis PTB-Bericht Th **12**, doi 10.7795/110.20220106 (2021).
[11] D. Seibt, “Schwingdrahtviskosimeter mit integrierter Ein-Senkkörper-Dichtemessverfahren für Untersuchungen an Gasen in größeren Temperatur- und Druckbereichen,” Fortschritt-Berichte, Reihe 6, Nr. 571, VDI-Verlag, Düsseldorf (2008).
[12] S. Herrmann, “Viskositäts- und Dichtemessungen an n-Butan und Isobutan in größeren Temperatur- und Druckbereichen,” Fortschritt-Berichte, Reihe 6, Nr. 615, VDI-Verlag, Düsseldorf (2015).
[13] U. Kochan-Eilers, “Measurements of the Viscosity of the Noble Gas Neon with a Vibrating-Wire Viscometer and Correlations of the Viscosity of Gases in the Limit of Zero Density,” Dissertation, Helmut-Schmidt-Universität/Universität der Bundeswehr Hamburg (2021).
[14] J. Wilhelm, “Development of a Viscometer with a Vibrating Wire for Investigations of Gases in Wider Ranges of Temperature and Density – Measurements of Argon, Krypton, and Propane,” Dissertation, Universität Rostock (1998).
[15] W. P. Mason, “Measurement of the Viscosity and Shear Elasticity of Liquids by Means of a Torsionally Vibrating Crystal,” Trans. ASME **69**, 359–370 (1947).
[16] C. Junker, “Novel Automated Torsionally Vibrating Crystal Viscometer for Liquids with Reference Quality,” Dissertation, Helmut-Schmidt-Universität/Universität der Bundeswehr Hamburg (2021).
[17] C. Junker and K. Meier, “Analysis of the Electrical Field in Viscosity Sensors with Torsionally Vibrating Quartz Cylinders,” J. Appl. Phys. **128**, 044505 (2020).
[18] P. R. Heyliger, C. Junker, K. Meier, and W. L. Johnson, “Effects of Crystalline Anisotropy on Resonant Acoustic Loss of Torsional Quartz Viscometers,” J. Acoust. Soc. Am. **151**, 2135–2148 (2022).
[19] R. F. Hafer and A. Laesecke, “Extension of the Torsional Crystal Viscometer to Measurements in the Time Domain,” Meas. Sci. Techn. **14**, 663–673 (2003).

Kapitel II
Künstliche Intelligenz und Intelligente Physische Systeme (KIIPS)

mit Beiträgen von

21strategies

Airbus Defence and Space GmbH

Airbus Operations GmbH

CTC GmbH

Emqopter GmbH

Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Hensoldt Sensor Systems

Hochschule für Angewandte Wissenschaften Hamburg

IT-Objects GmbH

Leibniz Universität Hannover

Robert Bosch GmbH

Technische Universität Bergakademie Freiberg

Third Element Aviation GmbH

Universität der Bundeswehr München

Universität Hamburg

University of Applied Sciences Augsburg

University of Duisburg-Essen

Weidmüller Interface GmbH & Co. KG

Vorwort zum dtec.bw-Dachprojekt
„Künstliche Intelligenz und Intelligente Physische Systeme (KIIPS)“

Befördert durch die rasante Leistungsentwicklung der Informations- und Kommunikationstechnologie zieht die Automatisierung in immer weitere technische Systeme in unserer Umgebung ein: Fahrzeuge, Gebäude, Fabriken und Verkehrssysteme werden dadurch „intelligent“, d.h. sie erbringen Leistungen der Reaktion, der Adaption und des vorausschauenden Handelns, die der Mensch bis vor kurzem nur sich selbst zugetraut hätte. Sensoren ermöglichen die Erzeugung und ständige Aktualisierung digitaler Modelle dieser Systeme. Diese Modelle können für die Steuerung und Optimierung verwendet werden, bis hin zu autonomen Systemfunktionen. Daraus ergibt sich eine Fülle potentieller methodischer und technologischer Innovationen. Insbesondere Methoden der Künstlichen Intelligenz (KI) können dabei eingesetzt werden, um die mit der Sensorik gesammelten großen Datenmengen zielgerichtet auszuwerten. Dies ist die methodische Klammer des Dachprojekts „Künstliche Intelligenz und Intelligente Physische Systeme (KIIPS)“. Auf diesen Themenfeldern wird an der HSU / UniBw H intensiv in Kooperation mit der Industrie geforscht, so dass hervorragende Möglichkeiten für den Ausbau von Forschungspartnerschaften und für den Technologietransfer gegeben sind. Die Anwendungsbereiche sind vielfältig, sie reichen von autonomen Luft-/Land-/Wasser-Fahrzeugen über Produktions-, Wartungs- und Transportprozesse und die Überwachung von Bauwerken bis zu körperlichen und kognitiven Unterstützungssystemen. Die Projekte im Dachprojekt „KIIPS“ befassen sich mit der Erforschung der methodischen und technologischen Grundlagen sowie den Möglichkeiten neuartiger Anwendungen.

Die zahlreichen Beiträge zu diesem Sammelband zeigen die Vielfalt der Projekte und der derzeitigen Arbeitsschwerpunkte darin: von Analysen des State-of-the-Art über Potentialstudien bis zu Darstellungen neuer Methoden sowie geplanter Arbeiten zur Validierung und Demonstration der Ergebnisse. Viele dieser Beiträge sind gemeinsam mit Co-Autoren der Kooperationspartner entstanden, was die sehr gute Zusammenarbeit mit den Forschungs- und Anwendungspartnern unterstreicht.

Ergänzend zu den Berichten aus den Einzelprojekten sind auch drei Beiträge enthalten, die von Autoren-Teams mehrerer Projekte gemeinsam erstellt wurden und Projekt-übergreifende Aspekte thematisieren.

Allen beteiligten Autoren des Dachprojekts "KIIPS" gebührt Dank dafür, dass sie – trotz der kurzen zur Verfügung stehenden Zeit im Spätsommer 2022 – bereit waren, zusätzlich zu den in den Projekten durchzuführenden Arbeiten und geplanten Veröffentlichungen die Beiträge zu diesem Sammelband zu erstellen.

Als Leiter des Dachprojekts „KIIPS“ möchte ich bei dieser Gelegenheit allen Projektleitungen und allen in den Projekten Mitarbeitenden, Studierenden und Forschungs- und Anwendungspartnern danken für ihr Engagement.

Allen Leserinnen und Lesern wünsche ich anregende Lektüre. Die Autorenteams freuen sich auf Fragen und Anregungen von Ihnen!

Hamburg, im November 2022

Alexander Fay

Dachprojektleiter „Künstliche Intelligenz und Intelligente Physische Systeme (KIIPS)“

Anwendung eines modellbasierten Rekonfigurationsansatzes und Vorstellung eines Konzeptes zur qualitativen Systemüberwachung für das Lebenserhaltungssystems (ECLSS) des COLUMBUS-Moduls der ISS

Benjamin Kelm*, Stephan Myschik
Institut für Aeronautical Engineering
Universität der Bundeswehr
München, Deutschland
*benjamin.kelm@unibw.de

Mark Tappe*, Oliver Niggemann
Institut für Automatisierungstechnik
Helmut-Schmidt-Universität
Hamburg, Deutschland
*mark.tappe@hsu-hh.de

***Zusammenfassung*—Cyber-physische Systeme (CPS) sind durch den Ausfall von Aktuatoren, Sensoren oder strukturellen Komponenten verschiedenen Fehlern ausgesetzt. Die zunehmende Größe und Komplexität moderner Systeme führt zu einer kosten- und zeitintensiven manuellen Fehlerbehandlung. Um Systeme in die Lage zu versetzen, sich selbständig an Fehler anzupassen, ist eine Rekonfiguration, d.h. die Identifizierung einer neuen gültigen Konfiguration, die den Betrieb wiederherstellt, notwendig.**

Dieser Beitrag stellt eine Erweiterung des kürzlich veröffentlichten Rekonfigurationsalgorithmus *AutoConf* und die Anwendung auf das Environmental Control and Life Support System (ECLSS) des COLUMBUS-Moduls an Bord der ISS vor. Die Implementierung stützt sich auf ein qualitatives Systemmodell (QSM), das in Aussagenlogik formuliert ist. Das zugehörige Erfüllbarkeitsproblem wird mit einem SAT-Solver gelöst. Die Erweiterung besteht aus drei Beiträgen, nämlich einer Implementierung des Gesundheitszustands, einem dynamischen Kausalgraphen und einer problemspezifischen Formulierung der seriellen Abhängigkeiten der Aktuatoren. Es wird eine statische Bewertung des erweiterten Rekonfigurationsalgorithmus für 73 Fehlerfälle vorgestellt, die ein breites Spektrum an Fehlern abdecken.

Des Weiteren wird ein Überwachungssystem vorgstellt, welches das zugrunde liegende qualitative Systemmodell (QSM) erweitert. Auf diese Weise wird eine Prädiktion des qualitativen Systemverhaltens ermöglicht, sodass eine direkte Evaluation der Rekonfigurationsmaßnahme vorgenommen werden kann.

***Stichworte*—Rekonfiguration, Fehlermanagement, Monitoring, qualitatives Systemmodell, SAT**

I. EINLEITUNG

Das Lebenserhaltungssystem (Environmental Control and Life Support System, ELCSS) der Internationalen Raumstation (ISS) kann als Cyber-Physical System eingestuft werden, da seine Mechanismen und Betriebsmodi durch einen Algorithmus gesteuert und überwacht werden. Obwohl auf Komponentenebene Verfahren zur Fehlererkennung, -isolierung und -rekonfiguration (FDIR) implementiert sind, gibt es keine systemweite automatische Fehlerbehandlung von ECLSS, was gegenwärtig ein manuelles und dauerhaftes Monitoring erfordert. Obwohl ECLSS als ein sehr robustes System konzipiert wurde, kam es in den letzten zehn Jahren zu Betriebsunterbrechungen aufgrund von unzureichend behandelten Sensor-, Struktur- und Aktuatorfehlern. Da das ECLSS für die Astronauten und Experimente an Bord der ISS von entscheidender Bedeutung ist, lohnt es sich, zu untersuchen, ob die Sicherheit und Zuverlässigkeit durch einen systemweiten Rekonfigurationsansatz erhöht werden kann.

Zur Bewertung dieser Hypothese wurde das Projekt (K)ISS ins Leben gerufen, welches einen Software-Stack zur Erkennung von Anomalien, der Bereitstellung einer Diagnose und Vorschläge zur Rekonfiguration für die automatische Fehlerbehandlung implementieren soll.

Die Aufgabe der Rekonfiguration besteht darin, das System von einer ungültigen in eine gültige Konfiguration zu überführen, d.h. ein System nach einem Fehler wiederherzustellen, indem die Systemkonfiguration automatisch so angepasst wird, dass der Betrieb innerhalb der Spezifikation des Systems aufrechterhalten werden kann [1].

In diesem Beitrag wird die Erweiterung und Anwendung des kürzlich veröffentlichten Algorithmus *AutoConf* von Balzereit und Niggemann [2] zur automatischen Rekonfiguration des ECLS-Systems vorgestellt. Der Algorithmus führt eine Rekonfiguration in zwei Schritten durch: Zunächst wird eine logische Formel erstellt, die das Rekonfigurationsproblem darstellt. In einem zweiten Schritt wird diese dann mit Hilfe eines SAT-Solvers gelöst, der eine alternative, valide Konfiguration als Ergebnis bereitstellt.

AutoConf implementiert einen solchen Ansatz, weist jedoch bei der Anwendung auf das vorliegende System einige Einschränkungen auf. Diese Einschränkungen sollen in dieser Arbeit adressiert und folgende Forschungsfrage beantwortet werden:

https://doi.org/10.24405/14539

Welche Erweiterungen des bestehenden Rekonfigurationsalgorithmus AutoConf sind notwendig, um das multiphysikalische System ECLSS hinreichend genau zu modellieren?

Im Allgemeinen wird eine Rekonfigurationsaufgabe durch eine Anomalieerkennung ausgelöst, gefolgt von einer Diagnose, die die fehlerhafte Komponente identifiziert. Diese Komponente steht dem System nicht mehr zur Verfügung und sollte daher aus der neuen Konfiguration ausgeschlossen werden. Weiter hängt bei physikalischen Prozessen die Wirksamkeit einer Eingangsgröße in der Regel von den Zustandsgrößen ab, die sie beeinflusst. Die Durchflussrichtung durch ein Ventil hängt z. B. von der Richtung des Druckunterschieds ab. Schließlich sind serielle Abhängigkeiten, bei denen eine Sequenz von Regelgrößen (z. B. Ventilstellungen) eingestellt werden müssen, um ein bestimmtes Ziel zu erreichen, in der realen Welt häufig anzutreffen. In dieser Arbeit sollen die beschriebenen Unzulänglichkeiten adressiert werden.

Dieser Beitrag ist wie folgt aufgebaut: Zunächst wird ein Überblick über verwandte Literatur gegeben und unser Ansatz in den Bereich der fehlertoleranten Regelung und modellbasierten Rekonfiguration eingeordnet. Als Nächstes beschreiben wir das vorliegende System, ECLSS, das für die Anwendung des Rekonfigurationsalgorithmus verwendet wird. Drittens werden die Erweiterungen des bestehenden *AutoConf*-Algorithmus vorgestellt, gefolgt von der Bewertung, bei der die statischen Rekonfigurationsergebnisse diskutiert werden. Der Beitrag endet mit einer Schlussfolgerung und einem Ausblick auf mögliche zukünftige Arbeiten.

II. Literatur Überblick

Dieser Abschnitt gibt einen Überblick über die Literatur in verwandten Forschungsbereichen: Der fehlertoleranten Regelung und qualitativen Ansätzen zur modellbasierten Rekonfiguration.

A. Fehlertolerante Regelung

Die fehlertolerante Regelung (Fault-Tolerant Control, FTC) befasst sich mit dem Entwurf von Reglern, die den Systembetrieb auch bei Vorliegen von Fehlern aufrechterhalten. Die Systemdynamik wird mit gewöhnlichen Differentialgleichungen modelliert; ein Regler verwendet dieses Modell, um kontinuierlich neue Systemeingaben zu berechnen, die das gewünschte Systemverhalten [3] festlegen. Blanke et al. [1] unterscheiden FTC-Techniken in *robuste* und *adaptive* Regelung. Robuste Regler bestehen aus einem einzigen Regler, dessen Parameter so gewählt werden, dass er mit möglichst vielen Fehlern umgehen kann. Im Falle eines Fehlers wird der Regler nicht angepasst, sondern eine a-priori Wahl des Reglers soll Toleranz gegenüber den meisten Fehlern ermöglichen. Adaptive Regler hingegen ändern ihre Parameter in Abhängigkeit von der Fehlersituation. Dadurch wird das Verhalten der Anlage an die Fehlersituation angepasst und die Auswirkungen des Fehlers können abgeschwächt werden.

Da FTC jedoch hauptsächlich mit quantitativen Modellen arbeitet, ist seine Anwendbarkeit auf hybride Systeme begrenzt: Das diskrete Systemverhalten, das sich aus verschiedenen diskreten Betriebsmodi ergibt, ist aufwändig, da für jeden diskreten Modus ein neues Regelgesetz definiert werden muss. Dies gestaltet den Umgang mit unvorhergesehenen Fehlern als äußerst schwierig.

B. Modellbasierte Rekonfiguration

Crow und Rushby [4] begründeten das Forschungsgebiet der modellbasierten Rekonfiguration. Sie erweiterten Reiters Diagnosealgorithmus [5] in Richtung der Identifikation einer Systemanpassung für diskrete Systeme. Diese Idee wurde in der weiteren Forschung aufgegriffen und führte zu einer Integration von KI-basierter Diagnose in Regelungsansätzen [6].

In ähnlicher Weise betonen Blanke et al. [1] die Notwendigkeit der Rekonfiguration als automatisierte Anpassung der Regelung eines Systems, um eine effiziente Fehlerbehandlung zu ermöglichen.

Ein Ansatz, der eine Rekonfiguration auf Basis von künstlicher Intelligenz (KI) implementiert, wurde von Balzereit und Niggemann [2] veröffentlicht. Ihr Algorithmus *AutoConf* basiert auf einem Solver für das Erfüllbarkeitsproblem der Aussagenlogik (SAT), der eine Eingabemaske identifiziert, die es cyber-physischen Produktionssystemen (CPPS) ermöglicht, die Produktion in Anwesenheit von Fehlern aufrechtzuerhalten. Da ihr Ansatz für CPPS entwickelt wurde, wird er in dieser Arbeit auf weitere Anwendungsbereiche ausgedehnt.

C. Qualitative Simulation

Qualitative Simulation befasst sich mit der Abschätzung des zukünftigen Systemverhaltens bei einer qualitativen Systembeschreibung. Anstelle von gewöhnlichen Differentialgleichungen werden Informationen über die Monotonie von Systemvariablen und Orientierungswerte, d.h. Werte, die signifikante Systemregionen darstellen, verwendet [7].

III. ECLS Systembeschreibung

Das Modul Columbus ist der größte Beitrag der Europäischen Weltraumorganisation (ESA) zur Internationalen Raumstation (ISS). Der Zweck von Columbus ist es, als einzigartige Plattform für verschiedene Forschungsbereiche zu dienen: Humanphysiologie, Biologie, Grundlagenphysik und vieles mehr. Betrieben wird das europäische Labor vom Columbus Kontrollzentrum des Deutschen Zentrums für Luft- und Raumfahrt (DLR) in der Nähe von München [8].

Das kritischste System des Columbus-Moduls ist das Lebenserhaltungssystem (ECLSS), dessen Topologie im Prozessablaufdiagramm in Abbildung 1 dargestellt ist. Es besteht aus einer Vorlauf- (ISFA) und einer Rücklaufgebläsebaugruppe (IRFA), einem redundanten Paar von Kabinengebläsebaugruppen (CFA 1/2), einem Temperaturregelventil (TCV), das den Luftstrom auf zwei redundante Kühl- und Kondensationskerne (Core 1 und 2) innerhalb des Kondensationswärmetauschers (CHX) verteilt, um die Luft zu kühlen und zu entfeuchten.

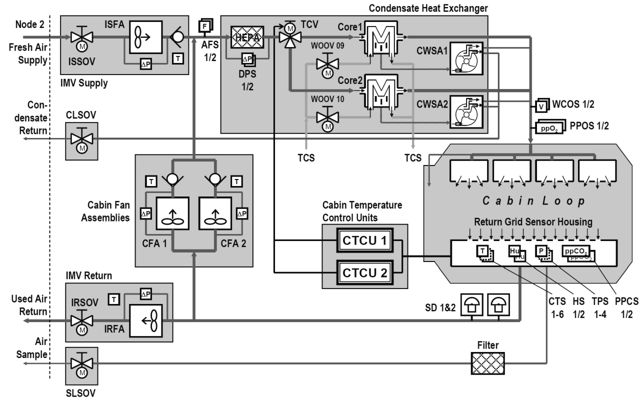


ABBILDUNG 1: PROZESSABLAUFDIAGRAMM DES ISS ECLS-SYSTEMS (CABIN LOOP) VON DOYÉ [8]

Der Luftstrom wird dann in die Kabine geleitet, wo er sich mit der Kabinenluft vermischt. Zur Auffrischung der Luft und zur Sicherstellung der Raucherkennung muss ein Mindestvolumenstrom an den Rauchmeldern (SD 1/2) vorbeigeführt werden. Der Rückstrom wird in Teilen vom ISFA an benachbarte Module zurückgeführt und zum Teil durch die CFAs direkt zurückgespeist. Das thermische Kontrollsystem (TCS) besteht aus den Kernen (Cores 1/2), dem Kühlmittel und den externen Wärmetauschern und wird von den redundanten Kabinentemperaturkontrollgeräten (CTCU 1/2) gesteuert.

Darüber hinaus gibt es mehrere Sensoren, die den Luftvolumenstrom (AFS), die Druckunterschiede zwischen den Lüftern und dem Filter (ΔP oder DPS), den Partialdruck von O_2 und von CO_2 (PPOS/PPCS), die Kabinentemperatur (CTS 1-6), die Luftfeuchtigkeit (HS 1/2) und den Gesamtdruck (TPS 1-4) messen.

IV. ENTWICKLUNG UND ANWENDUNG DES ERWEITERTEN LÖSUNGSALGORITHMUS

In diesem Abschnitt werden der Rekonfigurationsalgorithmus *AutoConf* und die für die Anwendung auf ECLSS erforderliche algorithmische Erweiterung kurz vorgestellt.

A. AutoConf — Der ursprüngliche Ansatz

AutoConf wurde kürzlich von Balzereit und Niggemann [2] vorgestellt und ist in zwei Schritte unterteilt: Im ersten Schritt wird eine logische Formel erstellt, die das Rekonfigurationsproblem darstellt. Im zweiten Schritt wird diese Formel mit einem SAT-Solver gelöst.

Für den ersten Schritt der Erstellung der logischen Formel, auch *qualitatives Systemmodell* (QSM) genannt, wird ein Kausalgraph G benötigt. Dieser Kausalgraph definiert qualitativ, welche Eingaben sich auf welche Zustände des Systems auswirken. Da *AutoConf* nur mit binären Eingaben (z.B. Ventil geöffnet oder geschlossen) arbeitet, definieren wir diese als $B = \{\boldsymbol{b}_1, ..., \boldsymbol{b}_k\}$. Der Kausalgraph wird zunächst in zwei Teilgraphen positiver $G^+ = (V, E^+)$ und negativer $G^- = (V, E^-)$ Einflüsse auf die Zustandsvariablen unterteilt. Die Knoten der Graphen bestehen aus den Zuständen und Eingaben $V = \{\boldsymbol{x}_1, ..., \boldsymbol{x}_n, \boldsymbol{b}_1, ..., \boldsymbol{b}_k\}$. Die Kanten im positiven Graphen E^+, die Eingänge und Zustände verbinden, zeigen eine signifikante *Erhöhung* dieses Zustands an, wenn dieser Eingang aktiviert wird: $E^+ = \{(\boldsymbol{b}_j, \boldsymbol{x}_i) \,|\, j \in \{1, ...k\}, i \in \{1, ...n\}\}$. In ähnlicher Weise entsprechen die Kanten des negativen Graphen E^- einer signifikanten Abnahme der Zustandsvariablen. Der Kausalgraph integriert somit eine qualitative Beschreibung der Systemdynamik.

Der Algorithmus durchläuft dann den Graphen und kodiert die Kausalität in Aussagenlogik. Dazu werden die Zustandsgrenzen $\Delta\boldsymbol{\epsilon}$ in die Symbole low_{x_i} und $high_{x_i}$ übertragen, die wahr sind, wenn x_i unterhalb der unteren Grenze oder oberhalb der oberen Grenze liegt. Diese Symbole bedeuten, dass bestimmte Eingänge aktiviert oder deaktiviert werden sollen. Überschreitet beispielsweise ein Reservoir seinen Grenzwert, so impliziert die Formel das Öffnen eines Abflusses *oder* das Schließen eines Zuflusses. Diese Bedingungen werden mit Hilfe der binären logischen Konnektiven (Negation [$\neg$], Konjunktion [$\wedge$] und Disjunktion [$\vee$]) formuliert.

Im zweiten Schritt wird ein logischer SAT-Solver verwendet, um die logische Formel mit Hilfe von maschinellen Beweisen zu lösen. Wenn die Formel *erfüllbar* ist, dann gibt es eine Zuordnung von Eingabevariablen, die die Formel wahr macht. Die Zuordnung entspricht der neuen Konfiguration, die erforderlich ist, um einen gültigen Systemzustand innerhalb einer bestimmten Rekonfigurationszeit Δt zu erreichen. Wenn die Formel nicht erfüllt werden kann, kann eine Rekonfiguration nicht durchgeführt werden und das System wird möglicherweise abgeschaltet.

B. AutoConf˙extd — Erweiterung von AutoConf für reale Systeme

Die Anwendung von *AutoConf* auf ECLSS - ein reales System - macht bestimmte Erweiterungen des Algorithmus notwendig, um das System adäquat zu beschreiben und rekonfigurieren. Daher werden wir zunächst die (kontinuierlichen) Systemzustände $\boldsymbol{x}$ und die (binären) Eingangsvariablen $\boldsymbol{b}$ für ECLSS definieren, die aus den folgenden Komponenten bestehen (vgl. Abschnitt III):

$$\boldsymbol{x} = [T_c, \phi_c, \dot{V}_{AFS}, p_c]^T \tag{1}$$

$$\begin{aligned}\boldsymbol{b} = [&b_{\mathrm{ISFA}}, b_{\mathrm{IRFA}}, b_{\mathrm{CFA}_1}, b_{\mathrm{CFA}_2}, ...\\ &b_{\mathrm{TCV}_1}, b_{\mathrm{TCV}_2}, b_{\mathrm{C}_1}, b_{\mathrm{C}_2}]^T.\end{aligned} \tag{2}$$

Es ist wichtig zu beachten, dass das Temperaturregelventil (TCV), das den Luftstrom auf die beiden Kerne aufteilt, als zwei binäre Eingänge behandelt wird. Die Aktivierung eines bestimmten Eingangs entspricht einer vorgegebenen maximalen Ansteuerung, z.B. bei den Ventilatoren kann das die maximale Dauerdrehzahl nach Vorgabe sein. Die Sollwerte mit zulässiger Abweichung der Zustände (im Regelbetrieb) sind gegeben durch

$$\boldsymbol{w} \pm \Delta\boldsymbol{\epsilon} = \begin{bmatrix} 295\,\mathrm{K} & -4\,\mathrm{K} & +3\,\mathrm{K} \\ 0.5 & -0.2 & +0.2 \\ 500\,\mathrm{m}^3/\mathrm{h} & -50\,\mathrm{m}^3/\mathrm{h} & +1000\,\mathrm{m}^3/\mathrm{h} \\ 101.3\times 10^3\,\mathrm{Pa} & -1300\,\mathrm{Pa} & +1700\,\mathrm{Pa} \end{bmatrix} \quad (3)$$

Im Folgenden werden die drei wichtigsten Erweiterungen vorgestellt, die für eine gültige Rekonfigurationsstrategie erforderlich sind.

1) Diagnose Implementierung: AutoConf enthält keine Implementierung einer Diagnose (im Folgenden health status bezeichnet) einer Komponente. Dies ist jedoch eine wichtige Funktion, um zu bestimmen, ob und wie ein System rekonfiguriert werden kann. So kann beispielsweise ein defekter Aktor nicht für die Rekonfiguration verwendet werden. Da wir das System nur über die Aktoren (Eingangsvariablen) manipulieren können, beschränken wir unseren Komponenten-Diagnose auf diese. Der health status wird als zusätzliche Einschränkung der bestehenden Formel implementiert. Wir definieren einen booleschen *health status* $\boldsymbol{h}$ entsprechend dem Eingabevektor in (2) und fügen dem *Systemmodell* (SM) die folgende zusätzliche Bedingung hinzu:

Algorithm 1 *AutoConf_GenSM_healthStatus*

1: **Eingang:** $X, B, low, high, POS, NEG, SM$
2: **Ausgang:** SM
3: **for** $j \in \{1, 2, ...k\}$ {für jeden Eingang $\boldsymbol{i}_k$} **do**
4: $\quad SM := SM \cup (\boldsymbol{h}_j \Rightarrow \boldsymbol{b}_j)$
5: **end for**
6: **for** $l \in \{1, 2, ...n\}$ {für jede Zustandsvariable $\boldsymbol{x}_l$} **do**
7: $\quad SM := SM \cup \left[\boldsymbol{high}_l \Rightarrow \bigvee_{\boldsymbol{b}_j \in NEG_l} (\boldsymbol{b}_j^0 \wedge \boldsymbol{h}_j) \Rightarrow \boldsymbol{b}_j)\right]$ {Beschränkung, die die Schließung eines Ausgangs verhindert}
8: $\quad SM := SM \cup \left[\boldsymbol{low}_l \Rightarrow \bigvee_{\boldsymbol{b}_j \in POS_l} (\boldsymbol{b}_j^0 \wedge \boldsymbol{h}_j) \Rightarrow \boldsymbol{b}_j)\right]$ {Beschränkung, die die Schließung eines Eingangs verhindert}
9: **end for**
10: **return** SM

Ausgehend von den Zustands- und Eingangsvariablen X und I, der Menge der abweichenden Zustandsvariablen low und $high$ sowie den positiven POS- und negativen NEG-Mengen der Eingänge und dem Systemmodell SM stellt die Zeile 4 des Algorithmus 1 sicher, dass nur intakte Eingänge verwendet werden, während die Eingänge bei der neuen Konfiguration automatisch geschlossen werden. Die nächsten beiden Zeilen verhindern ein Schließen der Abflüsse (negativer Eingang) bei einem fehlerhaften, hohen Systemzustand (vgl. Zeile 7) und ein Schließen der Zuflüsse bei einem niedrigen Systemzustand (vgl. Zeile 8). Die Verbindung mit der Variable für den health status ermöglicht es, fehlerhafte Eingänge unabhängig von dieser zusätzlichen Bedingung zu schließen.

2) Dynamischer Kausalgraph: ECLSS verfügt über intensive (Druck, Temperatur, Feuchtigkeit) und eine extensive Zustandsvariable (volumetrische Durchflussrate). Bei intensiven Zustandsvariablen können Zuflüsse sowohl einen positiven als auch einen negativen Einfluss haben. Ist z.B. die Zustromtemperatur von der ISS höher als in der Columbus-Kabine, so führt die Erhöhung der Lüftergeschwindigkeit zu einem Temperaturanstieg in der Kabine. Um intensiven Zustandsvariablen Rechnung zu tragen, werden wir die Inzidenzmatrix dynamisch definieren. Formal wird der Kausalgraph in Abhängigkeit vom Zustand des Systems und den Zuflussbedingungen verändert. Eine Kante ist Teil des positiven Teilgraphen $e_i \in E^+$, wenn sie signifikant, d.h. oberhalb eines bestimmten, durch Expertenwissen definierten Schwellenwertes, zum Anstieg der jeweiligen Zustandsgröße beiträgt.

3) Serielle Abhängigkeiten: Die dritte Erweiterung von *AutoConf* befasst sich mit den seriellen Abhängigkeiten von Aktuatoren. Das TCV muss beispielsweise einen Luftstrom durchlassen, damit die Wärmetauscher (Core 1/2) Wärme und Feuchtigkeit abführen können. Die erste serielle Bedingung bezieht sich auf die Notwendigkeit eines Mindestluftstroms durch die Kabine. Entweder ISFA oder die Umluftgebläse (CFAs) müssen aktiv sein und das TCV muss in einer der beiden Positionen geöffnet sein.

$$[b_{\mathrm{ISFA}} \vee (b_{\mathrm{CFA}_1} \vee b_{\mathrm{CFA}_2})] \wedge (b_{\mathrm{TCV}_1} \vee b_{\mathrm{TCV}_2}) \quad (4)$$

Mit den oben beschriebenen Erweiterungen ist der Algorithmus, den wir als *AutoConf˙extd* bezeichnen werden, in der Lage, ECLSS zu rekonfigurieren. Im Folgenden zeigen wir die Anwendung auf einen beispielhaften Fehlerfall, um den Prozess zu veranschaulichen.

V. Ergebnisse

Um den Rekonfigurationsalgorithmus und das Systemmodell zu validieren, wird eine statische Auswertung vollzogen. Dabei werden die Ergebnisse der Rekonfiguration für eine umfassende Fehlerfallliste mit der ursprünglichen Formulierung von *AutoConf* verglichen und die Abweichungen der Rekonfigurierbarkeit klassifizieren.

Tabelle I zeigt die Ergebnisse der Anwendung von *AutoConf˙extd* für 73 ausgewählte größtenteils hypothetische Fehlerfälle (vgl. dritte Spalte v. l.). Die Fehlerliste ist in verschiedene Fehlerkategorien unterteilt: Fehler, die nur einen Zustand oder Aktuator betreffen sowie Doppel- und Mehrfachfehler. Die Fehler werden weiter gemäß ihrer Art unterschieden in Grenzwertverletzung der Zustände (z. B. durch Leckagen oder externe Störungen), Aktuatorfehler (z. B. durch klemmende Ventile) und aus beiden vorangegangenen Kategorien kombinierte Fehler.

Die Liste der Fehlerfälle ist zwar nicht erschöpfend, deckt aber ein breites Spektrum an Fehlern ab. Etwa 78 Prozent der einzelnen Fehler sind rekonfigurierbar. Einige Einzelfehler (wie z. B. eine niedrige Temperatur) sind nicht direkt rekonfigurierbar, da ECLSS keine direkte Möglichkeit zur Erwärmung der einströmenden Luft bietet. Es ist wichtig anzumerken, dass der Ausfall eines beliebigen Stellglieds bewältigt werden kann, da das System eine mindestens zweifache Redundanz aufweist.

Die Doppelfehler bilden die größte Kategorie, von denen etwa 76 % rekonfigurierbar sind. Die doppelten Aktuator- und kombinierten Fehler weisen eine geringere Rekonfigurierbarkeit auf, da der Ausfall von zwei Aktuatoren desselben Typs

TABELLE I: VERGLEICH DER REKONFIGURATIONSERGEBNISSE FÜR DEN *AutoConf˙extd* UND *AutoConf* ALGORITHMUS - MIT UND OHNE HEALTH STATUS.

		AutoConf ˙extd	*AutoConf* mit health status			
Fehlerkategorie	**# Fälle**	**# rcfg.**	**# TP**	**# TN**	**# FP**	**# FN**
Einzelfehler	**19**	**15**	**11**	**4**	**4**	**0**
Grenzwertverletzung	9	7	5	2	2	0
Aktuatorfehler	5	5	5	0	0	0
kombinierte Fehler	5	3	1	2	2	0
Doppelfehler	**37**	**29**	**11**	**5**	**19**	**2**
Grenzwertverletzung	12	11	5	1	5	1
Aktuatorfehler	14	11	4	2	7	1
kombinierte Fehler	11	7	2	2	7	0
Mehrfachfehler	**16**	**9**	**2**	**2**	**11**	**1**
Summe	**73**	**53**	**24**	**11**	**34**	**3**
			33%	*15%*	*47%*	*4%*
		AutoConf ˙extd	*AutoConf* ohne health status			
Summe	**73**	**53**	**18**	**9**	**45**	**0**
			25%	*13%*	*63%*	*0%*

(z. B. beider Wärmetauscher) zum Verlust dieser Funktion führt. Verständlicherweise weisen die Fälle mit Mehrfachfehlern die geringste Rekonfigurierbarkeit von etwa 56 % auf, da mehrfache Grenzwertverletzung und Aktuatorfehler den Lösungsraum stark einschränken.

Weiter vergleicht die TABELLE I Ergebnisse des erweiterten Algorithmus *AutoConf˙extd* mit dem ursprünglichen Algorithmus *AutoConf*, sowohl *mit* als auch *ohne* die Implementierung des health status (rechte Spalte). Die Abweichungen werden als binäre Klassifizierung in Bezug auf das korrekte Ergebnis der Rekonfiguration durch *AutoConf˙extd* dargestellt. Die binäre Klassifizierung ist in den Spalten als True Positives (TP), True Negatives (TN), False Positives (FP) und False Negatives (FN) ausgewiesen.

Der Vergleich des ursprünglichen Algorithmus mit der Implementierung des health status wird für jede Fehlerkategorie im Detail dargestellt. Insgesamt wurden etwa 49 % der Fehlerfälle korrekt als entweder rekonfigurierbar (TP) oder nicht rekonfigurierbar (TN) identifiziert. Ein großer Teil (51 %) der gefundenen Konfigurationen durch *AutoConf* genügt jedoch nicht der erweiterten Formel, da sie weder den dynamischen Kausalgraphen noch die seriellen Aktuatorabhängigkeiten berücksichtigen (vgl. Abschnitt IV-B2).Die Anzahl der False Positives ist für die Kategorie der Mehrfachfehler besonders hoch, da der begrenzte Lösungsraum eine häufigere Verletzung der seriellen Aktorabhängigkeiten verursacht. False Negatives (FN) sind äußerst selten, da der ursprüngliche Algorithmus geringer beschränkt ist.

Der Vergleich für den ursprünglichen Algorithmus *ohne* health status Implementierung verschiebt das Ungleichgewicht weiter in Richtung der False Positives, da die Formel fehlerhafte Aktuatoren nicht berücksichtigt. Die Gesamtzahl der falsch

klassifizierten Fehler liegt bei etwa 63 Prozent, was auf eine deutlich verbesserte Fehlerbehandlung durch den erweiterten Algorithmus hinweist.

VI. QUALITATIVE SYSTEMÜBERWACHUNG

Die Auslegung der Rekonfiguration zur selbstständigen Anpassung an die verschiedenen Fehlerzustände, wurde in dem Abschnitt IV umfangreich dargelegt. Als Grundlage der Implementierung wurde ein qualitatives Systemmodell (QSM) auf Basis von Aussagenlogik verwendet. Dieses Vorwissen ermöglicht eine Darstellung der Wirkzusammenhänge für verschiedene Konfigurationen. Dabei steht vor allem das Erfüllbarkeitskriterium des Rekonfigurationsproblems im Vordergrund, nicht jedoch ein andauernder stabiler Betrieb. Die Systemüberwachung hat das Ziel das zugrunde liegende QSM zu erweitern, um das erwartete Verhalten nach einer Rekonfiguration zu evaluieren.

A. Qualitative Simulation und Systembeschreibung

Die Darstellung von physikalischen Abläufen mittels qualitativer Notation wurde von Benjamin Kuipers mit dem Simulationstool QSIM [7] umfangreich präsentiert und im Rahmen des Projektes wieder aufgegriffen, da sich der Ansatz bewährt hat [9], [10]. QSIM ermöglicht die Notation von qualitativen Differentialgleichungen (QDGL) mittels Parameter und Beschränkungen. Die Arbeit von Kuipers [7], [11] weicht dabei etwas von der Norm der klassischen Systemdarstellung ab, da Variablen von Ihm als Parameter und Funktionen als Beschränkungen deklariert werden. Diese Beschränkungen stellen die arithmetischen Zusammenhänge der Parameter untereinander dar, es wird zum Beispiel in Beschränkungen wie „Additiv“, „Multiplikativ“ oder „steigendes Verhalten“ unterscheiden. Die daraus resultierenden QDGL können dann das quantitative Systemverhalten abstrakt darstellen, indem quantitative Größen durch Wertebereiche oder konkrete qualitative Größen (auch Orientierungspunkte genannt) zu qualitativen Zustandswerten abstrahiert werden. Durch die zusätzliche Angabe einer Tendenz, ob ein steigendes, sinkendes oder stationäres Verhalten vorliegt, kann ein Ausgangspunkt für jeden Simulationsschritt definiert werden.

B. Beispiel zur qualitativen Darstellung

Für eine übersichtlichere Darstellung wird eine vereinfachte Systembeschreibung gewählt. Dadurch lässt sich die QDGL des Temperaturkreislaufes unter Einfluss einer konstanten Störgröße T_{St} wie folgt beschreiben:

$$T_{CAB} = T_{ISFA} + T_{CFA} + T_{CHX} + T_{St} \tag{5}$$

$$\dot{V}_{gesamt} = \dot{V}_{ISFA} + \dot{V}_{CFA} - \dot{V}_{IRFA} \tag{6}$$

$$\dot{V}_{CHX} = TCV * \dot{V}_{gesamt} \tag{7}$$

Dabei werden die Beschränkungen in der QSIM Notation beispielsweise als $M^{-}(T_{CHX}, \dot{V}_{CHX})$ definiert. Solche Funktionen werden dann für sämtliche Größen der QDGL aufgestellt und stellen die verschiedenen arithmetischen Zusammenhänge dar. Hierbei bezeichnet $M^{+}(A, B)$, bzw. $M^{-}(A, B)$ eine stetig steigende, bzw. fallende Funktion, bei der gilt: $A = f(B)$. Am Beispiel der Temperatur im Wärmetauscher wird die Funktion als negativ angesetzt, da bei steigendem Volumenstrom durch den Wärmetauscher die resultierende Temperatur zunehmend abnimmt: es wird mehr Luft gekühlt und die Temperatur fällt.

TABELLE II: ÜBERSICHT ÜBER DIE BEISPIELHAFTE VERÄNDERUNG DER QUALITATIVEN PARAMETER

Parameter	Initialwert	Übergangsphase 1	Übergangsphase k	Ausgangswert
T_{CAB}	$< (T_{CABnorm}, +\infty), inc >$	$< (T_{CABnorm}, +\infty), inc >$	$< (T_{CABnorm}, +\infty), dec >$	$< T_{CABnorm}, std >$
T_{CFA}	$< T_{CABnorm}, inc >$	$< (T_{CABnorm}, +\infty), inc >$	$< (T_{CABnorm}, +\infty), dec >$	$< T_{CABnorm}, std >$
T_{CHX}	$< T_{CHXnorm}, std >$	$< T_{CHXnorm}, std >$	$< T_{CHXnorm}, std >$	$< T_{CHXnorm}, std >$
$\dot{V}_{ISFA}$	$< 0, std >$	$< (0, +\infty), inc >$	$< (0, +\infty), inc >$	$< \dot{V}_{ISFA}, std >$
$\dot{V}_{IRFA}$	$< 0, std >$	$< (0, +\infty), inc >$	$< (0, +\infty), inc >$	$< \dot{V}_{IRFA}, std >$
$\dot{V}_{CFA}$	$< \dot{V}_{norm}, std >$	$< (0, \dot{V}_{norm}, dec >$	$< (0, \dot{V}_{norm}, dec >$	$< \dot{V}_{neu}, std >$

Betrachtet man nun die folgende Betriebssituation: In der Kabine wird eine Temperaturzunahme durch die Körperabwärme der Astronauten oder durch durchgeführte Experimente registriert. Unter Normalbedingungen würde die Temperaturregelung durch die Einstellung des TCV diese Änderung ausregeln können, jedoch wurde ein Defekt im Stellmechanismus diagnostiziert, wodurch eine Rekonfiguration eingeleitet wird. Die Rekonfigurationsmaßnahme beinhaltet nun das Zuführen der frischen und kälteren Zuluft über den ISFA und ein Ablassen der warmen Kabinenluft über den IRFA. Über die CFA wird die Temperatur dann angepasst, sodass die gewünschte Betriebstemperatur wieder erreicht wird.

Dieses Verhalten wird in der TABELLE II demonstriert. In den Spalten wird die Veränderung der Parameter in verschiedenen Phasen gezeigt, der Initialwert beinhaltet dabei schon den Einfluss der Störgröße, die hier selbst nicht weiter notiert wurde, da sie als konstant angesehen wird. Die Übergangsphase k ist eine Phase, die eintritt, sobald der Einfluss der Störgröße überwunden wurde.

An der qualitativen Veränderung der Kabinentemperatur T_{CAB} lässt sich erkennen wie die Temperaturen zunächst steigen und dann wieder fallen und sich letztendlich normalisieren. Dazu müssen die Volumenströme über den ISFA und den IRFA ebenfalls steigen bis sich ein stationärer qualitativer Zustandswert einstellt.

C. Anwendung des Qualitativen Modells zur Überwachung des Systemverhaltens

Die Verwendung eines qualitativen Systemmodells bringt jedoch zwei Probleme mit sich. Zum Einen können sehr komplexe kombinatorische Probleme entstehen, wenn alle möglichen Systemveränderungen berücksichtigt werden. Um diesem entgegen zu wirken, wird der Zeithorizont in dem die Evaluation erfolgt entsprechend limitiert, so dass eine Bewertung der unmittelbaren Auswirkungen stets erfolgen kann. Das andere Problem liegt in der Generierung des qualitativen Modells, da die QDGL und die Beschränkungen abhängig von dem jeweiligen Betriebsmodus des Systems sind. Wird eine Rekonfigurationsmaßnahme eingeleitet, führt dies zwangsläufig zu einer Änderung der qualitativen Systembeschreibung, sodass die aktuelle Konfiguration des Systems stets bekannt sein muss. Dies ist aber gegeben, da die Verwendung des qualitativen Models das Ergebnis der Rekonfiguration validiert. In den Fällen in denen eine Rekonfiguration nicht erforderlich ist, befindet sich das System in einem Normzustand, wodurch der Betriebsmodus ebenfalls bekannt ist. Somit verbleibt die Erstellung der QDGL als Problem. Dieses wurde mittels eines Systemidentifikationverfahrens [9] bereits thematisiert, sodass die Grundlagen hier Verwendung finden und der existierende Lösungsansatz am Lebenserhaltungsmodul angewendet werden kann. Durch das Erweitern des bekannten Ansatzes mittels Verfahren des maschinellen Lernens, wird eine umfangreiche qualitative Verhaltensanalyse ermöglicht.

Mit Hilfe dieser Qualitativen Überwachung lässt sich dann, die Auswirkung der Rekonfiguration bewerten, indem den Zuständen der Parameter eine Wertigkeit zugewiesen wird. Anhand der Messdaten, die über ECLSS bekannt sind, lassen sich die Transitionen der qualitativen Zustandsänderungen auswerten, wodurch eine probabilistische Abschätzung einer Transition getroffen werden kann. Dieses Wissen kann dann verwendet werden, um eine aktuelle Rekonfigurationsmaßnahme anzupassen oder zu validieren.

DANKSAGUNG

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt (K)ISS - Diagnose der ISS]

LITERATUR

[1] Mogens Blanke, Marcel Staroswiecki, Michel Kinnaert, and Jan Lunze. Diagnosis and fault-tolerant control. 2016.

[2] Kaja Balzereit and Oliver Niggemann. Autoconf: A new algorithm for reconfiguration of cyber-physical production systems. *IEEE Transactions on Industrial Informatics*, 2022.

[3] Bohui Wang, Bin Zhang, and Rong Su. Optimal tracking cooperative control for cyber-physical systems: Dynamic fault-tolerant control and resilient management. *IEEE Transactions on Industrial Informatics*, 17(1):158–167, 2021.

[4] Judith Crow and John M Rushby. Model-based reconfiguration: Toward an integration with diagnosis. In *Proceedings of the Ninth National Conference on Artificial Intelligence*, 1991.

[5] Raymond Reiter. A theory of diagnosis from first principles. *Artificial intelligence*, 32(1):57–95, 1987.

[6] Louise Travé-Massuyès. Bridging control and artificial intelligence theories for diagnosis: A survey. *Engineering Applications of Artificial Intelligence*, 27:1–16, 2014.

[7] Benjamin Kuipers. Qualitative simulation. *Artificial intelligence*, 29(3):289–338, 1986.

[8] Julian Doyé. An Advanced Columbus Thermal and Environmental Control System. In *SpaceOps 2012 Conference*, Stockholm, Sweden, June 2012. American Institute of Aeronautics and Astronautics.

[9] AC Cem Say and Selahattin Kuru. Qualitative system identification: deriving structure from behavior. *Artificial Intelligence*, 83(1):75–141, 1996.

[10] P.A. Fishwick, H.A. Simon, and P.A. Luker. *Qualitative Simulation Modeling and Analysis*. Advances in Simulation. Springer New York, 2012.

[11] Benjamin Kuipers. *Qualitative reasoning: modeling and simulation with incomplete knowledge*. MIT press, 1994.

Automated Anomaly Detection and Diagnosis of the Environmental Control System of the ISS

*Lukas Moddemann, Henrik Sebastian Steude,
Oliver Niggemann
Professorship Computer Science in Mechanical Engineering
Helmut Schmidt University
Hamburg, Germany
*lukas.moddemann@hsu-hh.de

Philipp Grashorn
Ground software development
Airbus Defence and Space
Bremen, Germany
philipp.grashorn@airbus.com

***Abstract*—Maintaining the operation of the International Space Station (ISS) is highly relevant, both socially and scientifically. To this end, corresponding telemetry data is continuously sent to Earth for monitoring and analysis. Due to the importance of life support systems for the survival of the astronauts, the data is currently monitored in laborious manual processes and analyzed for diagnosis in case of failures. Automated anomaly detection and diagnosis of these systems offer the potential not only to increase the efficiency of the engineers, but also to optimize the error-free operation of the space station and thus create more capacity for what the ISS was built for: science in space.**

In this paper we present the current state of development of Anomaly Detection (AD) and Diagnostic (DX) algorithms using data of the european part of the ISS, Columbus, as an example. We describe the state-of-the-art algorithms we implemented from the field of time series anomaly detection and model-based diagnosis and discuss the results in the concrete case. In addition, we discuss the respective advantages and disadvantages as well as the next steps in the project.

***Index Terms*—Machine Learning, Anomaly Detection, Cyber-Physical Systems, Diagnosis**

I. Introduction

The International Space Station ISS is a complex, technological system. In the event of a fault, e.g. a malfunction in the life support system, rapid and targeted identification of the cause of the fault is essential. Currently, data from roughly 20,000 sensors & signals within the European Columbus module is transmitted to the Columbus Operations Center (COL-CC) in Oberpfaffenhofen, where it is analyzed manually by a team of technicians. In case of occurrence of complex failures engineers of Airbus, the European industrial lead for the maintenance, commercialization and evolution of the Columbus, are involved into the resolution process. Maintaining the functionality of the ISS is of very high importance for scientific, political and economic reasons. The ISS currently represents the best opportunity for Europe to participate actively in space research. A central element for this is the automatic detection of dangerous or unwanted situations on the ISS and corresponding quick reactions. Examples of such anomaly detection and diagnosis problems in ISS operations are: (i) anomaly detection for the life support system and in resource consumption (power, data, cooling), (ii) diagnosing failure causes and proposing countermeasures. Such capabilities can directly help to reduce shift operations in control centers from 24x7 to 8x5 hours with on-call duty, a cost saving of about 75 %. Instead of time-consuming manual processes for analyzing the causes of errors, which take days, weeks or even months, intelligent assistance systems should point out possible correlations within seconds, make errors explainable and suggest solutions. This not only saves valuable time, but also sustainably improves the operational availability of the complex system. Overall, this will create more budget, time and availability for the actual purpose of the ISS: science. For this reason, two key components of the (K)ISS Project are to develop a software that is capable of detecting anomalies, i.e. symptoms, in the telemetry data of the Columbus module, as well as running a diagnosis, i.e. finding the root cause. A high level overview of the system to be developed is shown in Figure 1.

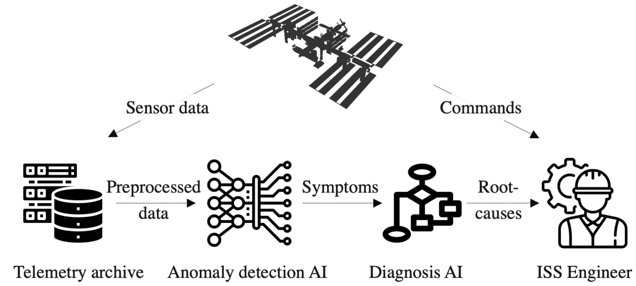


Figure 1. Overview of the (K)ISS project scope

In this contribution, we present the corresponding challenges, the current development status of the AD and DX use cases, discuss the results, and highlight the next steps and potential future research questions. The remainder of this paper is organized as follows: In the following Section, we present the two use cases in more detail and discuss the respective challenges, followed by a Section on the current state of research (Section III) regarding the two use cases and their challenges respectively. Section IV provides an overview of the solutions we are currently using to address the use case challenges, followed by the results in Section V. Finally, we conclude this paper in Section VI.

https://doi.org/10.24405/14540

II. Use Cases and Challenges

From an artificial intelligence (AI) perspective, AD and DX are two fundamentally different problems with currently incompatible approaches. As can be seen in Figure 1, sensor signals are the starting point for both problems. Based on these signals, indications of dangerous situations, i.e. anomalies, are identified. This is usually implemented by a neural network learning a model of normal behavior from the historical data. For new sensor data, anomalies can then be detected by comparing them to the prediction of the learned model.

However, often, a failure causes an anomaly at completely different locations in the system. For example, a malfunction in the ventilation system may mean that astronauts are no longer supplied with sufficient oxygen, but also that smoke detectors do not seem to work. Since the cabin air does not circulate independently in micro gravity, both the oxygen-rich air and the smoke must be actively distributed, otherwise neither CO2 saturation, which is dangerous for astronauts, can be detected in time, nor can smoke reach the smoke detector. Anomalies can also be due to various causes of failures. In the example of the ventilation system mentioned above, insufficient air circulation can be caused not only by too little fan power, but also by too much - for example, it has happened in the past that a redundant fan was mistakenly switched on and generated too much suction in the intake area, so that the protection grid was clogged by sucked-in parts. The task of the diagnosis is now to determine the root causes of the fault based on the anomalies. This allows faults to be repaired quickly and dangers to the ISS and crew to be avoided. However, this can no longer be done solely on the basis of data and simple limit monitoring. Hence, more advanced technologies like machine learning must be taken into account. Furthermore, it requires knowledge of system causalities, time dependencies and system structures: How does an error affect the overall system? How long does this take? Which system parts are independent of other system parts? Both the implementation of the AD as well the DX pose their own challenges, which we will describe in the following.

A. Anomaly detection

From a technical perspective, the task of anomaly detection in the example of the Columbus module is that timestamps in the multivariate sensor time series must be assigned to the groups “normal” and “not normal”. The output of the AD serves as input for the DX. That’s why it is important to know which signals or components behave the least normal, in the event of a fault or anomaly. In the concrete case, these requirements poses several challenges from the algorithmic point of view: First, the dataset is very large and needs to be analyzed with special tools such as distributed computing and time series databases. The Environmental Control and Life Support (ECLS) system alone, which is the first Columbus subsystem of interest, emits more than a thousand signals sampled at one Hertz. In total the Columbus module records and sends more than 20 thousand signals to ground. Secondly, the data are very sparsely labeled. A database of anomaly reports can be accessed, however, no accurate start and end times are given and sometime reoccurrences are not recorded in the database. Finally, and thirdly, the time series data are very unbalanced in two respects: anomalies in the Columbus module are (fortunately) very rare, and furthermore, the entire system is in a variety of states at different times, with very different frequencies.

B. Diagnosis

Tied to anomaly detection is the task of diagnosis to determine the root cause from anomalies or more precisely from symptoms. This task is performed by use of a logical solver in satisfiability (SAT) or satisfiability modulo theories (SMT) configuration. These solvers need a DAG describing the causal relations between system components as input. The anomaly detected by the previously performed anomaly detection algorithm is subsequently included as a symptom (not healthy) for the specific component in the rule base of diagnosis. Finally, the statements, that represent the rule basis of the diagnosis written in propositional logic will be checked for satisfiability using a logic solver where the output of the diagnostic service will be a minimal diagnosis for all conflict sets. The final outputs are important for the further investigation and to initiate a reconfiguration of the process or to be able to fix the system. According to the requirements listed above and from the perspective of model-based diagnosis the following challenges arise: First, to be able to build up a representation of the system in first order logic, the system description and the components’ causal relationships need to be known. This results in a high modeling effort and research from the design documentation, which is only partially available in digital form. Secondly, due to the complexity and the size of the ECLS system, different levels of a diagnosis have to be investigated. The levels can differ in diagnostics based on states, components or even on the lowest level of measurement sensor systems that have a causal relation on each other. Lastly, the engineering analysis reports that are part of the anomaly reports are very rare, which means that artificially generated anomalies have to be created within a simulation in order to be able to validate the diagnostic algorithm, including the check of health components for consistency and violation of intervention bounds.

III. State-of-the-Art

In this section, we provide an overview of the state of the art with respect to the challenges we described for the two use cases in the previous chapter.

A. State-of-the-art anomaly detection

Regarding the first challenge within anomaly detection, the handling of large data sets, there are some tools in the python ecosystem that have been developed exactly for this purpose, e.g. Spark [1], Dask [2], and Ray [3].

The detection of anomalies in multivariate time series with statistical models is a well established research field [4]. To address the second challenge, namely the lack of available labels, which are not sufficient for supervised learning, we limit ourselves to a group of models that can be trained without labels. For the detection of point anomalies in time series, the literature offers a variety of methods from different research areas of statistics and computer science, which have proven to be extremely well-performing. Well-known examples are the Gaussian Mixture models optimized with expectation maximization [5], one class support vector machines [6] and K-Means clustering, all of which use different measures or scores to distinguish normal data points from non-normal ones. The famous Autoencoder (AE) architecture for neural networks was first introduced in 1986 and is also well suited to detect point anomalies based on the reconstruction error [7]. Over the past few years, many new algorithms have been developed, which were specifically designed to identify anomalies in multivariate time series (sequence anomalies), many of which are based on deep neural networks. Among them are, for example, LSTM-based AEs [8], TCN-based [9] AEs, LSTM-base variational AEs [10] and BeatGAN [11], just to name a few.

As for the challenges of varying system modes, there is some work that attempts to extract the modes from the time series of data [12], [13]. If the system modes cannot be derived from the non-categorical signals, these models can be used to train individual models per system mode based on the mode prediction.

B. *State-of-the-art diagnosis*

To tackle the challenge of performing diagnosis on cyber-physical systems, that differ greatly in how detailed the system under consideration must be modeled in advance. Strong-fault models [14] specify faulty behavior modes for its system components and due to this, a change in the system results in an elaborate process to model the new fault signature combinations. In contrast, weak-fault models [15] make use of the normal behavior and are sometimes called a system with ignorance of abnormal behavior [16]. For this reason the description of the system needs to be formulated solely in the healthy state and therefore the approach is suitable for use cases with a huge amount of components like the ECLS system. Within diagnosis, a rule base for the identification of a root cause can be set up by different logical solvers, which are specifically designed to make a statement about whether a combination of propositional logical statements is satisfiable or unsatisfiable. Sympy [17] as a python library for symbolic mathematics offers an experimental assumptions system and uses a SAT solver for deduction of the exponentially increasing search space of component combinations. Z3 [18] is another state-of-the-art solver that makes use of SMT to be able to solve more complex formulas than solely boolean problems. To formulate the rules in first order logic, the system with its dependencies must be modeled. For this purpose, the research field of causalities has to be considered. According to our first challenge, a data-driven determination of the system dependencies has to be prioritized (e.g. Granger Causality [19], Transfer Entropy [20] or as a combination [21]). Another challenge is the determination of the level of diagnosis. In the field of cyber-physical systems, like ECLS, Struss [22] published a paper about the fundamentals of model-based diagnosis of dynamic systems. Within dynamic systems he proposed to capture the overall behavior of a hybrid system in a set of modes (or states) to be able to model the system. As mentioned above in the state of the art of anomaly detection, there are attempts to discretize hybrid data into modes [12], [13], which offer the opportunity to formulate logical rules according to the system modes for a diagnosis rule base.

IV. Solution

Although the (K)ISS project is still in an early phase, the first approaches have already been implemented and show promising results. As mentioned above, we focus on the ECLS system for validation and demonstration of the solutions. If the implementation is successful, the models will then be transferred to further subsystems (and eventually other systems, such as future space mission vehicles). In this section, we present the current development status of our AD and DX algorithms and discuss the results using the ECLS subsystem as a concrete example.

A. *Solution anomaly detection*

The general approach to detect anomalies in the telemetry data is, to train a model that “learns” the normal behavior of the subsystem. In this section we describe the dataset, the preprocessing steps and the model we use as a baseline for further developments.

1) Dataset: The data set of the ECLS subsystem, as well as the data sets of the other subsystems, consists of a number of continuous and categorical signals sampled at a frequency of one Hertz. The continuous signals represent sensor readings while the categorical ones represent discrete information such as switch positions, power status or commands. We call the time series dataset $\mathbf{X} \in \mathbb{R}^{T \times d}$ with T being the total number of timestamps (we use a time span of 2 years for the model training) and $d = c + k$ being the number of continuous signals c and the number of categorical signals k combined. In addition to the telemetry data, we collected the label information in order to validate our results. These labels were provided by the subject-matter-experts in form of a table holding the anomalies of the ECLS subsystem and the corresponding start and end timestamp. We use this table to split the dataset into a training set $\mathbf{X}_{train}$ and a validation set $\mathbf{X}_{val}$, such that $\mathbf{X}_{train}$ only holds “normal” time stamps. For the purpose of additional validation, other time windows were added to $\mathbf{X}_{val}$ at random, which do not contain known anomalies. Only $\mathbf{X}_{train}$ was used to update the model weights, so that only the “normal” state of the subsystem was “learned” by the model.

2) Preprocessing: For the preprocessing of the continuous signals, we use a default standard scaling. However, since we have a very large number of categorical signals ($k > 500$) the preprocessing of the corresponding signals is not as trivial. Applying the one-hot encoding [23], for example, would create over 1000 additional columns and therefore be very inefficient, in terms of storage, model weights and training time. Instead, we developed our own solution based on the frequencies of the unique combinations of the categorical values: Each unique combination of categorical entries that we observe in the training dataset is assigned to a unique ID. The unique IDs observed in less than 0.5% of the timestamps are assigned to a dummy category. We then apply one-hot encoding to the unique IDs and end up with only 300 categorical columns in the one hot encoded matrix. This dimensionality reduction is due to the fact, that there is a large number of different and rare unique combinations of the categorical signals. These combinations, however, would very likely be ignored by the model, since they do not contribute heavily to the negative average loss, which most ML models use as a training objective. All the preprocessing steps were implemented using Dask [2], such that it could run out of memory on several worker nodes in parallel.

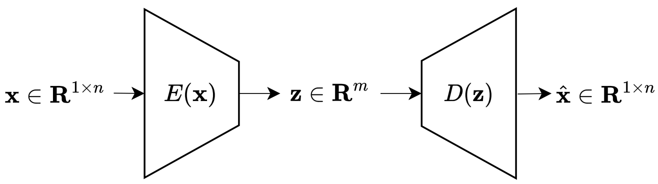


FIGURE 2. AUTOENCODER MODEL ARCHITECTURE

3) Model: According to the research questions of the (K)ISS-project, we aim at developing a deep learning based solution for the AD. For this reason we choose a vanilla AE [7] as a baseline model. The high-level overview of the model architecture is visualized in FIGURE 2. For every timestamp t the encoder E performs a highly non-linear dimensionality reduction $\mathbf{z} = E(\mathbf{x})$, such that $\mathbf{z} \in \mathbb{R}^m$ with $m \ll n$. The Decoder D maps the latent space variable $\mathbf{z}$ back to the original data space: $\hat{\mathbf{x}} = D(\mathbf{z})$. Both E and D are implemented as fully connected neural networks with LeakyReLU activations [24]. The model weights ($\sim$ 800k) were adjusted according to the mean squared error loss $\text{MSE}(\mathbf{X}, \hat{\mathbf{X}})$.

The model was trained on graphical processing units for 100 epochs.

B. Solution diagnosis

The first approach in solving the task of diagnosing the ECLS system of the Columbus module will be presented in the following. The key steps are the definition of a rule base, the check for health states and the output of possible diagnoses.

1) Rule base: The definition of the rule base will be done by system experts and on the basis of a system description given in FIGURE 3. To be able to use the qualitative model of the ECLS System a conversion in well-formed SAT expressions needs to be done. For this, directed acyclic graphs (DAG) [25] are useful for representing the causal relationships, including the processing flows within the system. The main advantage of DAGs is that multiple paths of processing streams can be modeled, expressing the ability for data to be processed in multiple ways. Based on the created DAG the components' relationships will be stored to a list of rules as the above-mentioned rule base.

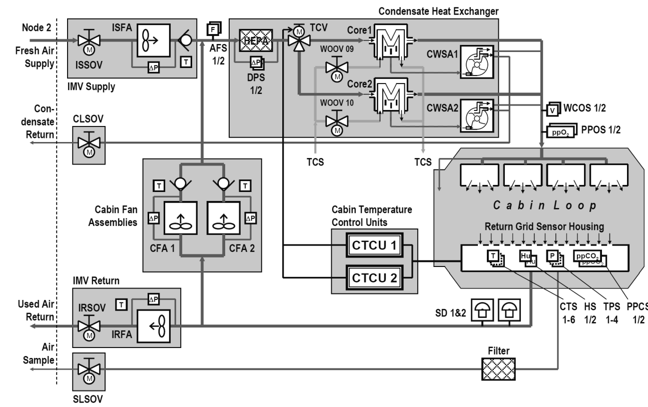


FIGURE 3. OVERVIEW OF THE ECLS SYSTEM [26]

2) Health states: As a next step to a diagnosis algorithm, the health states of the observable (measured) components will be investigated on its completeness according to the formulated rules. Therefore, a comparison between the information about detected anomalies, health states and list of rules will be carried out. However, in case of intentionally deactivated components, such as e.g. a deactivated Cabin Fan Assembly 1 (CFA1) according to FIGURE 3, this component must be excluded from the further diagnostic process. The reason here lies in the consideration of a possible automated reconfiguration on the basis of healthy and available components, to return the system back to an alternative working state and avoid a fatal downtime in e.g. ECLS. For this purpose, an exploration of the system in the actual operating state in case of a detected anomaly is performed. But not only this is under investigation. Another part of the algorithm takes also the check of the upper and lower bounds into consideration. If an anomaly is detected, the diagnosis algorithm will also check all other sensor measurements against its defined bounds to achieve an all-encompassing audit of the health states.

3) Diagnosis: Finally, in model-based diagnosis the formulated rule expressions will be checked on satisfiability. The result of consistency-based diagnosis is a set of possible fault hypothesis. The hypothesis will afterwards be discriminated by calculating the diagnosis of minimal faults.

V. RESULTS

This section describes the results obtained by the current versions of the AD and DX algorithms.

A. Results anomaly detection

The goal of the anomaly detection in the sense of our baseline model is to differentiate between "normal" and "non-normal" telemetry values or time points in the telemetry data stream of the ECLS system. The reconstruction error $e_t = \hat{\mathbf{x}}_t - \mathbf{x}_t = D(E(\mathbf{x_t})) - \mathbf{x}_t$ can be used as a suitable measure for this differentiation. Alerts might be generated as soon as the error hits a pre-defined threshold $e_t \geq e_{thresh.}$.

However, since e is usually rather noisy, further time series modelling, such as Kalman filtering [27] or simply applying a moving average on the time series e_t with $t \in [0, \ldots, T]$ might be necessary as a preprocessing step for the alerting algorithm.

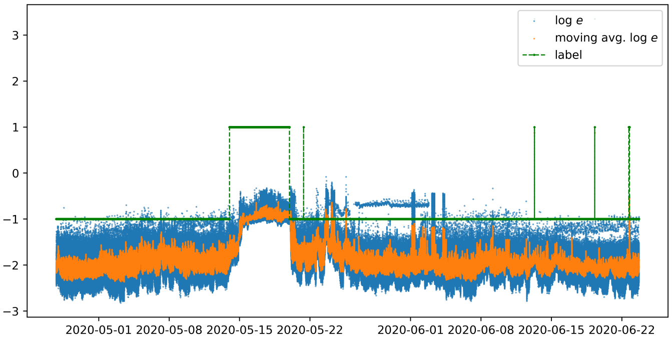


FIGURE 4. VISUALIZATION OF THE PERFORMANCE OF THE BASELINE MODEL FOR ANOMALY DETECTION

FIGURE 4 shows $\log(e)$ and its 5min moving averages over time for a random section of the dataset. The plot also holds the label information encoded as -1 for "normal" and 1 for "anomaly". We clearly see a correlation between the label signal and the moving average of the reconstruction error, especially at the longest anomaly around May 17th. This anomaly could have been detected e.g. by applying a simple threshold against the moving average. However, as expected, many of the very short anomalies can not be detected base on the moving average, even though the corresponding time stamps show a high reconstruction error. Another weakness of the baseline model is that it is not well suited to identify those signals that are primarily involved in the anomaly. However, this feature is needed to generate the output relevant for the diagnosis.

B. Results diagnosis

As a trigger event, the detected anomaly starts the diagnosis algorithm. The algorithm will first perform a preprocessing of rules, representing the system, and afterwards carry out a diagnosis on the symptoms of the system. In an exemplary investigation, a fault in the inter module ventilation supply (IMV Supply) was simulated. To identify the possible root causes in this example, two iterations were necessary. Within the first iteration it was possible to identify a partial diagnosis, namely the Condensate Heat Exchanger (CHX), that was accordingly excluded in a second iteration from the solution set of possible components to be diagnosed. The second iteration of diagnosis pointed out the remaining minimal diagnoses to explain the fault represented by CFA1 and CFA2. A discussion with the ECLS system expert validated the root cause analysis and confirmed it as a possible engineering analysis outcome.

VI. CONCLUSION

In this article, we have presented the current research status of the (K)ISS project. In particular, we focused on the areas of anomaly detection and diagnosis. For the anomaly detection, we introduced our base-line model, which is an autoencoder neural network. We showed that even this neural networks with the relatively simple architectures already deliver relatively good initial results in regard to the identification of faults. However, this baseline model also shows limitations, especially in the localization of the faults. For this reason, further steps are planned for the development of more advance models, such as (i) sequence models, (ii) system state aware models, and (iii) ensemble models to cover both short-term and log-term patterns. In addition, the rule-based alerting as well as the deployment strategy are also future research topics.

For diagnosis, we presented a first approach of model-based diagnosis. At this phase of the project, we showed an automated root cause analysis can be carried out, which causal dependencies of the system as input. These causal dependencies were extracted manually by use of the system description. However, the testing of the algorithm has to be investigated through additional failure simulations as test scenarios. Besides that, further steps into the proposals for diagnostic hypothesis based on past engineering analysis and confirmed root causes are needed, in order to give a user or a possible automated reconfiguration service a comprehensive database for the initiation of countermeasures. Besides that, further steps in the development to a recommender service for diagnostic hypothesis for a future user should be investigated, that matches the proposed diagnoses with those performed in the past. The recommender system can be seen as an additional service that takes past engineering analysis and approved diagnosis from the algorithm to be able to select the most promising diagnosis on an even larger information basis.

ACKNOWLEDGMENT

This research paper out of the project (K)ISS is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr.

REFERENCES

[1] M. Zaharia, R. S. Xin, P. Wendell, T. Das, M. Armbrust, A. Dave, X. Meng, J. Rosen, S. Venkataraman, M. J. Franklin, and Others, "Apache spark: a unified engine for big data processing," *Commun. ACM*, vol. 59, no. 11, pp. 56–65, 2016.

[2] M. Rocklin, "Dask: Parallel computation with blocked algorithms and task scheduling," in *Proceedings of the 14th python in science conference*, vol. 130, 2015, p. 136.

[3] P. Moritz, R. Nishihara, S. Wang, A. Tumanov, R. Liaw, E. Liang, M. Elibol, Z. Yang, W. Paul, M. I. Jordan, and Others, "Ray: A distributed framework for emerging {AI} applications," in *13th USENIX Symposium on Operating Systems Design and Implementation (OSDI 18)*, 2018, pp. 561–577.

[4] A. Garg, W. Zhang, J. Samaran, R. Savitha, and C.-S. Foo, "An evaluation of anomaly detection and diagnosis in multivariate time series," *IEEE Trans Neural Netw Learn Syst*, vol. PP, Aug. 2021.

[5] A. P. Dempster, N. M. Laird, and D. B. Rubin, "Maximum likelihood from incomplete data via theEMAlgorithm," *J. R. Stat. Soc.*, vol. 39, no. 1, pp. 1–22, Sep. 1977.

[6] B. Schölkopf, R. C. Williamson, A. Smola, J. Shawe-Taylor, and J. Platt, "Support vector method for novelty detection," *Adv. Neural Inf. Process. Syst.*, vol. 12, 1999.

[7] D. E. Rumelhart, G. E. Hinton, and R. J. Williams, "Learning internal representations by error propagation," California Univ San Diego La Jolla Inst for Cognitive Science, Tech. Rep., 1985.
[8] P. Barmpoutis, P. Papaioannou, K. Dimitropoulos, and N. Grammalidis, "A review on early forest fire detection systems using optical remote sensing," *Sensors*, vol. 20, no. 22, p. 6442, 2020.
[9] S. Bai, J. Zico Kolter, and V. Koltun, "An empirical evaluation of generic convolutional and recurrent networks for sequence modeling," http://arxiv.org/abs/1803.01271v2, 2018.
[10] D. Park, Y. Hoshi, and C. C. Kemp, "A multimodal anomaly detector for Robot-Assisted feeding using an LSTM-Based variational autoencoder," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 1544–1551, Jul. 2018.
[11] B. Zhou, S. Liu, B. Hooi, X. Cheng, and J. Ye, "BeatGAN: Anomalous rhythm detection using adversarially generated time series," in *IJCAI*, 2019, pp. 4433–4439.
[12] N. Hranisavljevic, A. Maier, and O. Niggemann, "Discretization of hybrid CPPS data into timed automaton using restricted boltzmann machines," *Eng. Appl. Artif. Intell.*, vol. 95, p. 103826, Oct. 2020.
[13] V. Fortuin, M. Hüser, F. Locatello, H. Strathmann, and G. Rätsch, "Deep self-organization: Interpretable discrete representation learning on time series," in *ICLR*, 2019.
[14] P. Struss and O. Dressler, ""physical negation" integrating fault models into the general diagnostic engine." in *IJCAI*, vol. 89, 1989, pp. 1318–1323.
[15] J. De Kleer, A. K. Mackworth, and R. Reiter, "Characterizing diagnoses and systems," *Artificial intelligence*, vol. 56, no. 2-3, pp. 197–222, 1992.
[16] A. Feldman, G. Provan, and A. Van Gemund, "Approximate model-based diagnosis using greedy stochastic search," *Journal of Artificial Intelligence Research*, vol. 38, pp. 371–413, 2010.
[17] A. Meurer, C. P. Smith, M. Paprocki, O. Čertík, S. B. Kirpichev, M. Rocklin, A. Kumar, S. Ivanov, J. K. Moore, S. Singh *et al.*, "Sympy: symbolic computing in python," *PeerJ Computer Science*, vol. 3, p. e103, 2017.
[18] L. d. Moura and N. Bjørner, "Z3: An efficient smt solver," in *International conference on Tools and Algorithms for the Construction and Analysis of Systems*. Springer, 2008, pp. 337–340.
[19] C. W. Granger, "Investigating causal relations by econometric models and cross-spectral methods," *Econometrica: journal of the Econometric Society*, pp. 424–438, 1969.
[20] T. Schreiber, "Measuring information transfer," *Physical review letters*, vol. 85, no. 2, p. 461, 2000.
[21] C. Kühnert, *Data-driven methods for fault localization in process technology*. KIT Scientific Publishing, 2013, vol. 15.
[22] P. Struss, "Fundamentals of model-based diagnosis of dynamic systems," in *IJCAI (1)*, 1997, pp. 480–485.
[23] K. Potdar, T. S. Pardawala, and C. D. Pai, "A comparative study of categorical variable encoding techniques for neural network classifiers," *Int. J. Comput. Appl. Technol.*, vol. 175, no. 4, pp. 7–9, 2017.
[24] B. Xu, N. Wang, T. Chen, and M. Li, "Empirical evaluation of rectified activations in convolutional network," *arXiv preprint arXiv:1505.00853*, 2015.
[25] J. Pearl, *Causality*. Cambridge university press, 2009.
[26] J. Doyé, "An advanced columbus thermal and environmental control system," in *SpaceOps 2012*, 2012, p. 1292285.
[27] G. Welch, G. Bishop *et al.*, "An introduction to the kalman filter," 1995.

Technische und methodische Analyse von automatisierten Kompaktlagern

Nicolas Fauvé, Florian Jaehn
Fakultät WiSo / Institut für Operations Research / Professur für BWL, insbesondere Management Science und Operations Research
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Hamburg, Deutschland
{nicolas.fauve, florian.jaehn} @hsu-hh.de

Moein Azizpour, Benedikt Hein, Alice Kirchheim
Fakultät MB / Institut für Automatisierungstechnik / Professur Technologie von Logistiksystemen
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Hamburg, Deutschland
{moein.azizpour, benedikt.hein, alice.kirchheim} @hsu-hh.de

Simone Neumann
Fakultät BWL / Juniorprofessur für BWL, insbesondere nachhaltige Logistik- und Mobilitätssysteme / Universität Hamburg
Hamburg, Deutschland
simone.neumann@uni-hamburg.de

***Kurzfassung* – Die Nutzung von Lagerflächen steht technisch bedingt im Zielkonflikt zwischen einem hohen Flächennutzungsgrad und schnellen Zugriffsmöglichkeiten auf die gelagerten Einheiten. Um einen hohen Flächennutzungsgrad zu erzielen, müssen freie Räume minimiert werden. Freie Räume wiederum werden zum Zugriff auf Ladungseinheiten benötigt, so dass der Zielkonflikt offensichtlich wird. Im Bereich von Kleinteilelagern, die auf einem Raster basieren (grid-based storage system), gab es in den letzten Jahren erfolgreiche Markteinführungen, die einen nie dagewesenen Flächennutzungsgrad ermöglichen. Wir werden in diesem Beitrag sowohl auf bestehende derartige Kompaktlager wie zum Beispiel AutoStore und Ocado eingehen, als auch weitere technische und organisatorische Umsetzungen zukünftiger Kompaktlager beleuchten. Denn während AutoStore und Ocado nur von oben auf das Lager zugreifen, und dadurch ein LiFo-Prinzip (Last in – First out) umsetzen, sind auch Systeme darstellbar, die eine seitliche Ein- und Auslagerung ermöglichen können. Sofern sich der Ein- und Auslagerungsprozess nicht nur auf eine Seite beschränkt, lässt sich dadurch deutlich flexibler vom meist nachteiligen LiFo-Prinzip abweichen und so die Durchlaufzeit verringern.**

Stichworte – Kompaktlager, Kleinteilelager, Blocklager AutoStore, Ocado

Nomenklatur

AMR	Autonomous Mobile Robot
CNN	Faltungsneuronales Netzwerk (Convolutional Neural Network)
FiFo	First in – First out
KLT	Kleinladungsträger
LiFo	Last in – First out
LMAPF	Lifelong Multi-Agent Path Finding
MAPF	Multi-Agent Path Finding
ROP	Robotic-Order-Picking

I. Einleitung

Wir betrachten in diesem Beitrag eine bestimmte Gattung von Kompaktlagern. Unter einem Kompaktlager verstehen wir dabei ein Lagerhaltungssystem, bei dem ein Großteil der möglichen Positionen im Lager (mindestens 50 %) keinen unmittelbaren Zugriff erlaubt, sondern im Falle eines voll ausgelasteten Lagers erst durch Umpositionierung anderer gelagerter Einheiten angesteuert werden kann. Während dieses Prinzip bei homogenen Gütern Standard ist, wurde und wird bei der Lagerung verschiedener Einheiten oft auf einen schnellen Zugriff auf einzelne Lagereinheiten oder Ladungsträger Wert gelegt. Kompaktlager mit nicht-homogenen Ladungseinheiten sind meist automatisiert, wobei es durchaus auch Kompaktlager ohne jegliche Automatisierung gibt [1]. Neben der Automatisierung beschränken wir uns auf grid-based storage Systeme. Das sind Kompaktlager, die in äquidistanten Abständen Platz für jeweils eine Ladungseinheit, meist KLT, haben. Dies eröffnet zahlreiche Möglichkeiten bei der technischen Umsetzung, insbesondere der Stapelbarkeit von Ladungseinheiten, aber auch bei der methodischen Analyse derartiger Systeme, allen voran die einfache, koordinatenbasierte Beschreibung einer jeden Position im Lager. Nachteilig ist dabei, dass die zu lagernden Einheiten in ihrer Größe beschränkt sind auf das zugrundeliegende Raster, bzw. die darin enthaltenen KLTs. So gesehen beschränken wir uns auf Kleinteilelager, wobei diese Beschränkung nicht in der Methodik liegt, sondern in dem Umstand, dass in der Praxis fast nur Kleinteilelager entsprechenden Größenbeschränkungen unterworfen sind.

Unter die genannte Kategorie von Kompaktlagern fallen die sich auf dem Markt befindenden Lösungen von AutoStore und Ocado [2]. Diesen Systemen ist gemein, dass sie ausschließlich mittels AMR auf das Lager zugreifen, und dass sie skalierbar sind. Das zugrundeliegende Raster kann auf örtliche Gegebenheiten angepasst werden und auch im Zeitverlauf mit relativ geringem Aufwand vergrößert oder verkleinert werden. Weiterhin ist diesen Systemen gemein, dass die AMRs (grün) stets von nur einer Seite auf das Lager (rot) zugreifen, meist von oben, siehe Abbildung 1. Die Pickstation (orange) ist in der Regel ebenerdig angeordnet, so dass die AMRs über einen oder mehrere Aufzüge die Strecke von den Zugriffspunkten zur Pickstation und zurück überwinden können.

https://doi.org/10.24405/14541

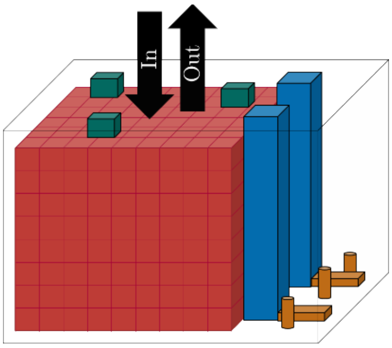


ABBILDUNG 1: ARBEITSWEISE DER KOMPAKTLAGER VON AUTOSTORE UND OCADO.

Dadurch wird – bei Zugriff von oben – zumindest für jeden einzelnen Stapel das LiFo-Prinzip angewendet. Weiter unten gelagerte Einheiten können dem Lager nur mit deutlich höherem Aufwand entnommen werden als in den oberen Positionen gelagerte Einheiten. Einheiten, die lange im Lager verweilen, „sacken" durch die Umstapelungen zur Entnahme anderer Einheiten im Zeitverlauf nach unten, so dass selten nachgefragte Einheiten tendenziell in tieferen Positionen zu finden sind. Insbesondere wenn die Lagerverweildauer der Einheiten aber eine sehr geringe Varianz hat, wenn also alle Lagereinheiten eine nahezu gleich lange Zeitspanne gelagert werden, wirkt sich das nachteilig aus, da dadurch die meisten Einheiten von tiefen Positionen zu entnehmen sind. Es entsteht somit die paradoxe Situation, dass eine eigentlich wünschenswerte Situation mit geringer Varianz (und dadurch besserer Planbarkeit) hier zum höchsten Aufwand bei der Entnahme von Ladungseinheiten führt.

Entsprechend ist die Untersuchung von Kompaktlagern mit Zugriff von (mindestens) zwei Seiten auf das Lager von großem Interesse, da es die Nachteile des LiFo-Prinzips vermeiden kann.

Im Folgenden werden wir die technischen und planerischen Herausforderungen für den Einsatz automatisierter Kompaktlager herausarbeiten (Abschnitt II). Anschließend beschreiben wir die Herausforderungen eines seitlichen Zugriffs im Abschnitt III. In Abschnitt IV benennen wir die bisherigen Antworten, die sich dazu bereits in der Literatur finden. Dieser Beitrag schließt mit einer kurzen Zusammenfassung.

II. TECHNISCHE UND PLANERISCHE HERAUSFORDERUNGEN IM BETRIEB EINES AUTOMATISIERTEN KLEINTEILEKOMPAKTLAGERS

Aus technischer Sicht ist die Konstruktion des Lagers inklusive der Hebe- und Senkvorgänge der KLTs von großer Bedeutung. Wir legen unseren Fokus allerdings auf die Steuerung und Navigation der AMRs sowie auf die (möglichst) autonome Handhabung von Stückgütern.

Aus planerischer Sicht gilt es das Befüllen des Lagers sowie Entnahmen aus dem Lager zu organisieren. Nicht zuletzt können auch Umlagerungsvorgänge außerhalb von Stoßzeiten die Leistungsfähigkeit des Lagers beeinflussen.

A. Steuerung und Navigation der AMRs

In heutigen Logistiksystemen mit automatisierten Flurförderzeugen erfolgt die Navigation zumeist anhand vorgegebener Pfade, beispielsweise realisiert durch Lasernavigation oder induktive Leitspuren. Diese Art der Navigation ist zweckmäßig, wenn Flurförderzeuge auf den immer gleichen Routen verfahren und die Anzahl der Flurförderzeuge einen stetigen Materialfluss auf diesen Routen erlaubt. Anders verhält es sich in robotisierten Logistiksystemen, in denen hunderte AMRs eingesetzt werden [3], die zwischen dynamisch zugewiesenen Start- und Zielpunkten verfahren. Hierbei wird für jeden AMR ein Pfad berechnet, welcher Informationen aus einer Karte der zu durchquerenden Umgebung berücksichtigt. Bei der Berechnung dieser Pfade kann es vor allem bei steigender Zahl von gleichzeitig navigierenden Robotern zu unvorhergesehenen Überschneidungen zwischen den geplanten Pfaden kommen.

Der Einsatz von AMRs in Logistiksystemen hat erst in den letzten Jahren stark zugenommen. Aus diesem Grund gibt es immer noch einen Bedarf, die Pfadplanung zu verbessern [4]. Eine heute in der Forschung aktiv diskutierte Möglichkeit, die Pfadplanung durchzuführen, ist der Einsatz von MAPF-Verfahren [5]. Übertragen auf Logistiksysteme wird bei MAPF-Verfahren jeder AMR von einem mobilen Agenten repräsentiert. Das Ziel der MAPF-Verfahren ist eine Pfadplanung für mehrere Agenten unter der Bedingung, dass jeder Agent sein Ziel erreicht und die Agenten nicht kollidieren.

Der Nutzen von MAPF-Verfahren wird bereits für den Einsatz in der Logistik diskutiert [6, 7]. Da die dort gewählten Anwendungsfälle reale Logistiksysteme nur unzureichend abbilden, ist bisher eine Bewertung der Eignung von MAPF-Verfahren in diesen Systemen nicht möglich. Innerhalb des Teilprojekts wurden daher zuerst qualitative Bewertungskriterien und industrienahe Anwendungsszenarien entwickelt [8], die künftig anhand bekannter MAPF-Verfahren evaluiert werden sollen.

Eine Erweiterung der MAPF-Verfahren ergibt sich durch eine direkte Zuweisung neuer Aufträge. Die daraus entstehenden Herausforderungen werden als LMAPF bezeichnet. Bisherige Betrachtungen und Vergleiche von LMAPF-Verfahren für industrienahe, logistische Anwendungsszenarien gibt es nicht. Daher wurden drei LMAPF-Verfahren evaluiert [9].

In der weiteren Projektlaufzeit werden die bisher evaluierten Verfahren für die Anwendung in intralogistischen Szenarien adaptiert. Darüber hinaus wird aktuell an der Anwendung von Deep Reinforcement Learning Ansätzen für den Einsatz von LMAPF-Problemen geforscht.

B. Autonome Handhabung von Stückgütern

Die stetig wachsende Branche des E-Commerce erfordert schnelle und kosteneffiziente Lösungen für die Kundenauftragsbearbeitung und Kommissionierung. In der Logistik nimmt der Einsatz von ROP in Anbetracht des Demografiewandels und der hohen Kosten pro Kommissionierung zu. Allerdings gibt es noch keine vollautomatischen, in der Industrie einsetzbaren ROPs in der Logistik, und ihre Flexibilität in Bezug auf die Form und die Kategorie der zu kommissionierenden Objekte ist stark eingeschränkt. Um dieses Problem zu überwinden, bauen neuere ROP-Ansätze auf den Fortschritten im Bereich Computer Vision auf, insbesondere auf der Verwendung von Deep Learning und CNN.

Der Einsatz von Deep Learning erfordert allerdings eine große Menge an domänenspezifisch gelabelten Daten. In bestimmten Bereichen gibt es allerdings nach wie vor wenig qualitativ hochwertig gelabelte Daten. Ein Ansatz innerhalb dieses Teilprojekts ist die synthetische Datengenerierung für den Einsatz von ROPs – insbesondere im Bereich des E-Grocery. Erste Ansätze zeigen den Erfolg, statistisch der Realität entsprechende Daten zu generieren [10]. In der Zukunft wird der Einsatz von CNN für diese Daten getestet und mit den Ergebnissen mit noch zu erhebenden gelabelten Daten aus dem Labor verglichen.

C. *Einlagerungsstrategien*

Einlagerungen von KLTs in das System sind bei Kompaktlagern hinsichtlich des Zielortes technisch meist stark beschränkt. Unabhängig davon, ob ein Zugriff nur von oben oder auch von einer Seite möglich ist, gibt es nur wenige Positionen, die ohne einen Umlagerungsvorgang erreichbar sind. Ein Umlagerungsvorgang, um einen KLT an einem gewünschten Zielort zu positionieren, ist, wenn überhaupt, nur zu Zeiten sinnvoll, in denen deutlich weniger Entnahmen als möglich stattfinden. Nichtsdestotrotz bestehen gewisse Freiheitsgrade. Die entsprechenden Entscheidungen werden in der Praxis meist regelbasiert getroffen. Oft liegt dabei eine gedankliche Unterteilung des Lagers in Zonen zugrunde, denen in Rahmen einer ABC-Analyse Ladungsträger zugeordnet werden können.

Auch in der wissenschaftlichen Literatur wird das Befüllen eines Lagers nur rudimentär behandelt, wie etwa aus dem Übersichtsartikel von Boysen et al. 2019 ersichtlich ist [11]. Der weitaus größere Teil der Literatur zu Kompaktlagern beschäftigt sich mit Entnahmestrategien. Hinsichtlich des Befüllens werden grundsätzliche Fragestellungen wie eine mögliche Zoneneinteilung behandelt oder die Fragestellung, ob mehrere Einheiten eines zu lagernden Gutes im Lager (traditionell) nahe beieinander positioniert werden sollten, oder, wie in (teil-)automatisierten Lagern heutzutage üblich, innerhalb des Lagers verteilt (scattered storage).

D. *Entnahmestrategien*

Wir gehen bei den Kompaktlagern davon aus, dass hier ein scattered storage umgesetzt wird. Dadurch ergeben sich komplexitätstheoretisch sehr herausfordernde Fragestellungen. Selbst in einer statischen Situation, also in einem Zustand, in dem sämtliche zukünftig zu erledigende Aufträge bekannt sind und keinerlei Betriebsstörungen zu beachten sind, sind sowohl das Order Picking als auch das Batching schwierig zu lösende Fragestellungen.

Beim Order Picking geht es darum, einzelne Entnahmeaufträge, die in der Regel aus mehreren zu entnehmenden Einzelteilen bestehen, durchzuführen. Dazu ist zunächst festzulegen, aus welchen KLTs die einzelnen Teile für einen Auftrag zu entnehmen sind. Da ein Produkt ja für gewöhnlich in mehreren KLTs vorhanden ist (und jeder KLT unterschiedliche Produkte enthält), gibt es hier Wahlmöglichkeiten. Allein die Fragestellung, welche KLTs zu entnehmen sind, so dass die Anzahl der zu entnehmenden KLTs eines einzelnen Auftrags minimiert wird, ist eng mit dem streng NP-schweren Mengenüberdeckungsproblem verwandt. Sobald die entsprechenden KLTs ausgewählt sind, gilt es festzulegen, in welcher Reihenfolge die KLTs zu entnehmen sind. Hierbei zeigt sich, je nach Ausgestaltung des Lagers und bedingt durch die von den AMRs zurückzulegenden Wegstrecken, eine große Ähnlichkeit mit dem Problem eines Handlungsreisenden.

Oft werden die Aufträge aber nicht sukzessive abgearbeitet, sondern zu einem Batch zusammengefasst. Beim Batching geht es dann also darum, einzelne Entnahmeaufträge zusammenzufassen, so dass diese zeitgleich und dadurch schneller bearbeitet werden können. Dabei ist ein meist limitierter Platz an den Kommissionierstationen ein begrenzender Faktor. Selbst wenn für jeden Einzelauftrag festgelegt wurde, welche KLTs zur Erfüllung herangezogen werden, ist das Batching ob des begrenzten Platzes an den Kommissionierstationen komplexitätstheoretisch als schwer anzusehen, was sich aus der Ähnlichkeit zum Behälterproblem (bin packing) ergibt. Unnötig zu erwähnen, dass ein hierarchischer Ansatz, der zunächst jedem Auftrag die entsprechenden KLTs zuordnet und erst dann die Zusammensetzung der Batches bestimmt, Optimierungspotential auslässt, da es ja möglicherweise KLTs gibt, die mehr als nur einen Auftrag bedienen können.

Die Annahme statisch vorhandener Aufträge und deren Erfüllung ohne weitere Erkenntnisse und Änderungen im Zeitverlauf ist dabei sicher praxisfern. Gewöhnlich ist mit einer dynamischen Situation zu rechnen, in der laufend weitere Aufträge eingehen und während des laufenden operativen Prozesses mit eingeplant werden müssen.

Die wissenschaftliche Literatur hat sich ausführlich mit Entnahmestrategien beschäftigt [11, 12, 13, 14], wobei die automatisierten Kompaktlager bisher weitgehend unberücksichtigt bleiben [15]. Insbesondere für den Fall mit Zugriffsmöglichkeiten von zwei Seiten besteht hier also ein hoher Forschungsbedarf.

E. *Umlagerungsstrategien*

Hochautomatisierte Lager erlauben es aufgrund des geringen, bzw. zum Teil sogar nur im Falle von Störungen vorhandenen Personalbedarfs (dark factory), zumindest vom Grundsatz her, rund um die Uhr betrieben zu werden. Für gewöhnlich gibt es aber starke zeitliche Schwankungen hinsichtlich der Auftragseingänge und Belieferungen. Daher ist auch immer mit Zeiten zu rechnen, in denen die AMRs nicht voll ausgelastet sind. Diese Zeiten können dazu genutzt werden, die sich im Lager befindenden KLTs vorausschauend umzupositionieren, so dass Prozesse in Stoßzeiten schneller ablaufen können. Im Kontext von Containerstellflächen wird dafür der Begriff „housekeeping“ verwendet [16].

Je nachdem, ob bereits konkrete oder statistische Informationen über zukünftige Aufträge vorliegen, werden die Umlagerungen die vorliegenden Informationen nutzen, um die bald benötigten KLTs nahe der Zugriffsstelle zu positionieren oder um eine Zoneneinteilung umzugestalten oder auch wiederherzustellen.

Weil derartige Umlagerungen nicht unmittelbar notwendig sind, spielt hierbei eine Berücksichtigung der dabei verbrauchten Energie eine besondere Rolle. Jedes Anheben eines KLTs verbraucht gewichtsabhängig Energie, die bei zahlreichen Umpositionierungen zu einem erheblichen Kostenfaktor beim housekeeping werden kann. Es ist zu erwarten, dass der Nutzen einer Umlagerung mit der Anzahl der Umlagerungen abnimmt, und somit ab einem bestimmten Zeitpunkt die Energiekosten den Nutzen übersteigen.

III. Ergebnisse zu Kompaktlagern mit seitlichem Zugriff

Auch wenn es nach unserem Wissen noch kein automatisiertes Kompaktlager auf dem Markt gibt, das den Zugriff auch von der Seite erlaubt, ist eine entsprechende technische Umsetzung möglich. Wir beschränken uns dabei zunächst auf den Fall, in dem die Einlagerungen der KLTs von oben durchgeführt werden, die Entnahme allerdings von der Seite, siehe Abbildung 2.

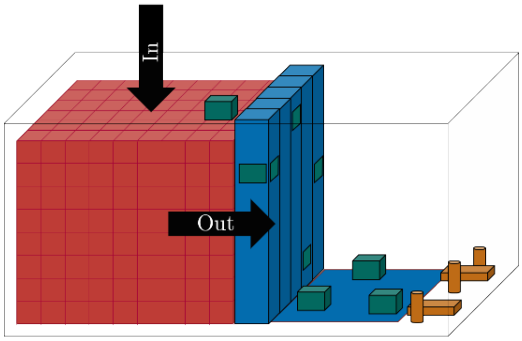


Abbildung 2: Arbeitsweise des Kompaktlagers mit seitlichem Zugriff.

Zu den technischen Anforderungen gehört es hierbei, dass zur Entnahme eines KLTs zunächst ein Gang geschaffen werden muss, durch den der KLT dann befördert wird. Dies ließe sich einerseits durch seitliches Verschieben der sich im Weg befindlichen KLTs erreichen. Dadurch müssen aber auch die seitlich angrenzenden KLTs sowie sämtliche sich darüber befindenden KLTs verschoben werden. Andererseits wäre auch das Anheben der sich im Weg befindenden KLTs denkbar, so dass sich eine Gasse bildet, siehe Abbildung 3. Wie der KLT dann genau dem Lager entnommen wird, beispielsweise durch ein Fördersystem, automatisch durch ein leichtes Gefälle, oder mittels AMR, ist hinsichtlich der Lagerorganisation von geringerer Bedeutung.

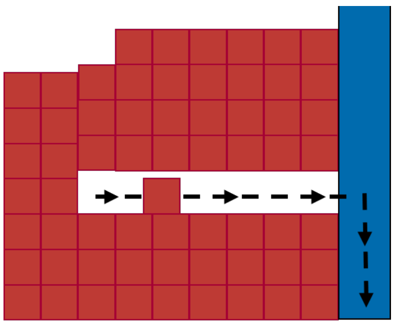


Abbildung 3: Seitliche Entnahme eines KLT.

Der große Vorteil des Zugriffs von zwei Seiten ist, dass die KLTs das Lager durchlaufen und Umpositionierungen (auf Kosten des Bildens einer Gasse) entfallen. Umpositionierungen können zum Teil verheerende Folgen haben und in Kürze benötigte KLTs aus einer gut erreichbaren Position selbst bei vorausschauendem Umpositionieren zwangsläufig an ungünstige Positionen verschieben. Stattdessen wird hierbei, zumindest annähernd, ein FiFo-System implementiert.

Die bei diesem System zu beantwortenden und im vorherigen Abschnitt aufgeführten Fragestellungen scheinen in der wissenschaftlichen Literatur bisher kaum betrachtet worden zu sein. Einen ersten Schritt in diese Richtung liefern Fauvé und Neumann [17], die sich konzeptionell mit der Frage auseinandersetzen, welche Kosten bei der Einlagerung und der Entnahme eines KLTs in Abhängigkeit von dessen Position entstehen. Hierbei wird unterschieden zwischen dem Zeitverbrauch und den Energiekosten. Bei dem Zeitverbrauch ($t_{retrieve}$) spielen insbesondere die horizontale ($t_{hor,x}$) und vertikale Bewegung ($t_{ver,y}$) und fixe Entnahmezeiten (t_{pick}) eine Rolle. Dies ist in Abbildung 4 dargestellt. Bei den Energiekosten ist neben der Bewegung des zu entnehmenden KLTs vor allem das Bilden der Gasse ausschlaggebend.

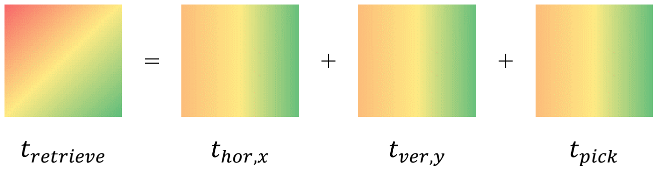


Abbildung 4: Zeitverbrauch einer seitlichen Entnahme im Kompaktlager.

Basierend auf der genannten Kostenverteilung haben Fauvé und Jaehn [18] ein stark vereinfachtes Ein- und Auslagerungsmodell erstellt, das das Lager in separate zweidimensionale Schichten unterteilt, die unabhängig voneinander betrachtet werden können. Für unterschiedliche Parameter der Kostenfunktion werden Optimalitätskriterien für die zugrundeliegenden Optimierungsprobleme bestimmt.

IV. Zusammenfassung

Trotz ihrer hohen Durchdringung im Markt sind automatisierte Kompaktlager in der Literatur bisher eher stiefmütterlich behandelt worden. In diesem Beitrag haben wir einige der Forschungsfelder dargestellt, die in diesem Zusammenhang bearbeitet werden sollten. Darüber hinaus haben wir die Bedeutung eines Zugriffs auf ein Kompaktlager von (mindestens) zwei Seiten beleuchtet und erste Forschungsergebnisse dazu präsentiert.

Danksagung

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [AuLoKomp – Autonomes, flexibles IntraLogistik-Kompaktlager]

Literatur

[1] A. Foroughi, N. Boysen, S. Emde und M. Schneider, „High-density storage with mobile racks: Picker routing and product location," *Journal of the Operational Research Society,* Bd. 72, Nr. 3, p. 535–553, 2021.

[2] K. Azadeh, R. De Koster und D. Roy, „Robotized and Automated Warehouse Systems: Review and Recent Developments," *Transportation Science,* Bd. 53, Nr. 4, p. 917–945, 2019.

[3] P. R. Wurman, R. D'Andrea und M. Mountz, „Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses," *AIMag,* Bd. 29, Nr. 1, pp. 9-20, 2008.

[4] Í. R. Da Costa Barros und T. P. Nascimento, „Robotic Mobile Fulfillment Systems: A survey on recent developments and research opportunities," *Robotics and Autonomous Systems,* Bd. 137, Nr. 103729, 2021.

[5] R. Stern, N. Sturtevant, A. Felner, S. Koenig, H. Ma, T. Walker, J. Li, D. Atzmon, L. Cohen, T. K. S. Kumar, E. Boyarski und R. Bartak, *Multi-Agent Pathfinding: Definitions, Variants, and Benchmarks,* 2019.

[6] M. Damani, Z. Luo, E. Wenzel und G. Sartoretti, „PRIMAL2: Pathfinding Via Reinforcement and Imitation Multi-Agent Learning - Lifelong," *IEEE Robotics and Automation Letters,* Bd. 6, Nr. 2, pp. 2666-2673, 2021.

[7] L. Xie, H. Li und N. Thieme, „From Simulation to Real-World Robotic Mobile Fulfillment Systems," *Logistics Research,* Bd. 12, Nr. 1, 2019.

[8] B. Hein, M. Wesselhoeft, M. Azizpour, A. Kirchheim und J. Hinckeldeyn, „Bewertung von Multi-Agent Path Finding Verfahren für deren Einsatz in robotisierten Logistiksystemen," *Logistics Journal: Proceedings 2022.18,* 2022.

[9] B. Hein, M. Wesselhoeft, A. Kirchheim und H. Johannes, „Towards Industry-Inspired Use-Cases for Path Finding in Robotic Mobile Fulfillment Systems," *27th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA),* 2022.

[10] M. Azizpour, N. Namazypour und A. Kirchheim, „Synthetic Data Generation for Robotic Order Picking," *zur Veröffentlichung eingereicht.*

[11] N. Boysen, R. De Koster und F. Weidinger, „Warehousing in the e-commerce era: A survey," *European Journal of Operational Research,* Bd. 277, Nr. 2, p. 396–411, 2019.

[12] N. Correll, K. E. Bekris, D. Berenson, O. Brock, A. Causo, K. Hauser, K. Okada, A. Rodriguez, J. M. Romano und P. R. Wurman, „Analysis and Observations From the First Amazon Picking Challenge," *IEEE Trans. Automat. Sci. Eng. (IEEE Transactions on Automation Science and Engineering),* Bd. 15, Nr. 1, p. 172–188, 2018.

[13] C. Eppner, S. Höfer, R. Jonschkowski, R. Martín-Martín, A. Sieverling, V. Wall und O. Brock, „Lessons from the Amazon Picking Challenge: Four Aspects of Building Robotic Systems," *Robotics: Science and Systems XII 2016,* 2016.

[14] T. van Gils, K. Ramaekers, a. Caris und R. B. d. Koster, „Designing efficient order picking systems by combining planning problems: State-of-the-art classification and review," *European Journal of Operational Research,* Bd. 267, Nr. 1, pp. 1-15, 2018.

[15] K. Azadeh, R. De Koster und D. Roy, „Robotized Warehouse Systems: Developments and Research Opportunities," *ERS-2017-009-LIS,* 2017.

[16] A. Ehleiter und F. Jaehn, „Housekeeping: Foresightful container repositioning," *International Journal of Production Economics,* Bd. 179, p. 203–211, 2016.

[17] N. Fauvé und S. Neumann, „Optimizing Storage and Retrieval in Fully Automated Grid-Based Storage Systems," *zur Veröffentlichung eingereicht.*

[18] N. Fauvé und F. Jaehn, „Grid based storage systems with access from two sides," *Arbeitspapier.*

Funktions- und Messprinzip des Absetz- und Datenerfassungskonzepts eines Systems zur flugmobilen Netzdatenerfassung

Alexander Schulzke*, Mirco Alpen, Joachim Horn
Professur für Regelungstechnik
Helmut-Schmidt-Universität /
Universität der Bundeswehr Hamburg
Hamburg, Deutschland
alexander.schulzke@hsu-hh.de

Hanifa Mukka, Marc F. Meyer, Detlef Schulz
Professur für Elektrische Energiesysteme
Helmut-Schmidt-Universität /
Universität der Bundeswehr Hamburg
Hamburg, Deutschland
hanifa.mukka@hsu-hh.de

Fridolin Popov, Sebastian Lehmen, Nils Gageik
Emqopter GmbH
Würzburg, Deutschland
nils.gageik@emqopter.de

***Zusammenfassung*—Dieses Paper ist im Rahmen des Projekts *Digitalisierte, rechtssichere und emissionsarme flugmobile Inspektion und Netzdatenerfassung mit automatisierten Drohnen (kurz DNeD)* entstanden. Ziel des Projekts ist die Erforschung und Erprobung eines intelligenten flugfähigen Systems, welches automatisiert Freileitungen inspiziert und dabei befähigt ist, einen Sensor zur Erfassung elektrischer Größen im Mittel- und Hochspannungsnetz auf einer Freileitung abzusetzen.**
Dieses Paper stellt das Hardware-Design der zu entwickelnden automatisierten Flugplattform (engl. unmanned aerial system, (UAS)) und der abzusetzenden Messsonde sowie die regelungstechnischen Ansätze zur Steuerung des UAS in den Vordergrund.

***Index Terms*—UAS, Autonomie, Netzimpedanz**

I. Einleitung und Motivation

Automatisierte Roboter im allgemeinen und Multikopter, welche im Volksmund gern als Drohnen bezeichnet werden, im speziellen, besitzen ein enormes wirtschaftliches und gesellschaftliches Potential. Dieses zeigt sich bereits in vielen Bereichen. Diese unmanned aerial systems (UAS) werden aktuell als Überwachungswerkzeug, als Transporteinheit oder auch für Aufgaben im Bereich der Geodäsie oder zur optischen Inspektion von Infrastruktur eingesetzt, und tragen dort zu einer deutlichen Steigerung der Effizienz und Kostenersparnis bei.

Das Projekt DNeD knüpft an die bisherige Einsatzpraxis von UAS im Bereich der Inspektionsaufgaben und bei Netzbetreibern an. So hat man beispielsweise im Projekt Voltair [2], welches im Rahmen des österreichischen Energieforschungsprogramms gefördert wurde, untersucht, wie die Schadensdetektion an Freileitungen, Transformatoren, Schaltanlagen und Umspannwerken durch Verwendung eines UAS und speziell abgestimmter Sensorik verbessert werden kann. Insbesondere die Erkenntnisse in Zusammenhang mit der Detektion und Positionierung des Fluggeräts relativ zur Freileitung können Einfluss auf die technische Umsetzung des im Rahmen von DNeD zu entwickelnden Funktionsmusters haben.

Die Firma *Linebird* aus den USA hat ein System auf den Markt gebracht, welches einen Sensor zur Strommessung kurzzeitig mit Hilfe eines UAS an die Leitung hält [6]. Der Sensor hängt dabei an einem halbsteifen Gestänge etwa 1 m unterhalb des Kopters und wird für maximal einige Sekunden an die Leitung gebracht. Eine Entkopplung von Sensor und Fluggerät findet dabei nicht statt. Über den Grad und die Art der Automatisierung des Systems geht aus den genutzten Quellen keine Information hervor.

Im Rahmen von DNeD soll erstmals ein Messsystem zur Erfassung elektrischer Größen auf einer zu prüfenden bestromten Freileitung abgesetzt werden, um langfristige Messungen durchführen zu können. Dadurch wird der Einsatzbereich von Multikoptern deutlich erweitert, da nicht nur ein sicherer automatisierter Flug innerhalb elektrischer Streufelder möglich wird, sondern auch das präzise Absetzen von Lasten auf beweglichen Untergründen.

Bedarf für ein solches System besteht aber nicht nur bei Stromnetzbetreibern, sondern ebenso bei Bahnnetzbetreibern, die ebenfalls über eine eigene Netzinfrastruktur verfügen.

Die weiteren Ausführungen sind wie folgt strukturiert. In Kapitel II wird das avisierte Hardwaredesign des UAS vorgestellt. Anschließend folgt eine Übersicht über mögliche Reglerstrukturen zur Positions- und Trajektorienfolgeregelgung des Kopters. Kapitel IV widmet sich der Darstellung von Herausforderungen und Lösungsansätzen beim Aufbau der abzusetzenden Messsonde.

II. Hardwaredesign des Trägersystems

Das Trägersystem ist als Hexakopter in X-Konfiguration ausgeführt, hat eine Spannweite von $1,85\,\mathrm{m}$ und ein Abfluggewicht von ca. $15\,\mathrm{kg}$. Mit seinen sechs bürstenlosen

https://doi.org/10.24405/14542

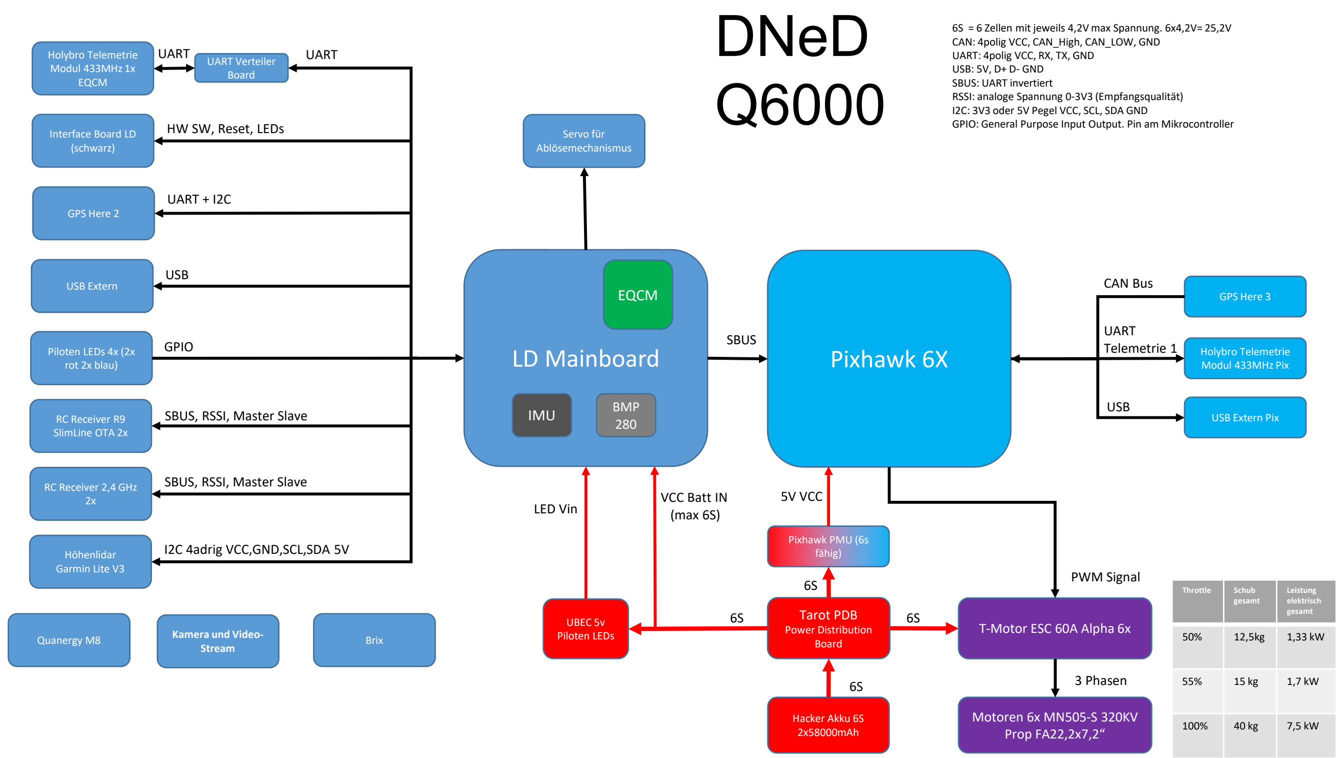


ABBILDUNG 1. GEPLANTES HARDWARE DESIGN DES MULTIKOPTERS

Gleichstrommotoren [7] und 22 Zoll Propellern, erzeugt das Trägersystem einen maximalen Schub von $40\,\text{kg}$, wobei die Motoren zusammen etwa eine elektrische Leistung von $7,5\,\text{kW}$ aufnehmen. Für den Schwebeflug bei Windstille benötigen die Motoren etwa $1,7\,\text{kW}$ elektrische Leistung. Das System besteht aus einem flugfähigen Basiskopter, die durch Zusatzsysteme für erweiterte Funktionen, wie Autonomie, ergänzt ist.

A. *Basiskopter*

Der Basiskopter ist nach bewährter Architektur aufgebaut und kann durch den Piloten per Fernsteuerung gesteuert werden. Bei einem Fehlverhalten der Zusatzsysteme, kann der Pilot diese jederzeit abschalten und die Steuerung der Drohne übernehmen. Zusätzlich erlaubt dieser Aufbau eine schrittweise Inbetriebnahme und Erprobung des Systems.
Als Flugsteuerung kommt eine Pixhawk 6X mit der neusten PX4-Firmware zum Einsatz 8, diese ermöglicht die Simulation von Hard- und Software in the Loop und bietet eine ROS2-Schnittstelle. Die Pixhawk 6X, welche in ABBILDUNG 1 zentral angeordnet ist, verfügt neben zwei Prozessoren über drei inertiale Messeinheiten (IMU), zwei Barometer und einen Kompass. Die inertialen Messeinheiten und Barometer sind mit separaten Bussen angebunden. Durch jede inertiale Messeinheit erhält die Flugsteuerung Messdaten zur Bewegung in allen sechs kinematischen Freiheitsgraden. Die Barometer messen den statischen Absolut-Luftdruck zur Höhenbestimmung. Als zusätzliche Sensoren sind auf dem, per CAN-Bus angebundenen, Here3-Modul ein GPS-Empfänger, ein Kompass und eine weitere inertiale Messeinheit verbaut.
Als weiteres Eingangssignal erhält die Flugsteuerung das Signal der Fernsteuerung, das von den Empfängern über das LD-Mainboard an die Pixhawk 6X geleitet wird. Um eine erhöhte Störsicherheit zu erhalten, sind das UAS und die Fernsteuerung über jeweils zwei $2,4\,\text{GHz}$- und $868\,\text{MHz}$-Empfänger in Master/Slave-Hierarchie verbunden. Sollte die Funkverbindung zwischen dem Fernsteuerungs-Sender und allen Empfängern dennoch abbrechen, kann der Kopter, je nach eingestelltem Failsafe-Modus, unter anderem automatisch die Landung einleiten oder zum Startpunkt zurückkehren.
Die acht übertragenen Signale enthalten neben den Steuersignalen des Piloten auch die Wahl des Flugmodus. Durch die Auswahl eines manuellen Flugmodus kann das System, im Falle eines Fehlverhaltens, auch ohne GPS und Kompass oder Barometer sicher geflogen werden.
Als Ausgangssignal erzeugt die Flugsteuerung sechs PWM-Signale, die mit einzelnen Signalleitungen, die Drehzahlregler (ESC) der Antriebsmotoren ansteuern. Durch die Konfiguration als Hexacopter kann das System den Ausfall von bis zu zwei Motoren, abhängig von deren Position, verkraften. Im Allgemeinen kann der Ausfall eines Motors kompensiert werden.
Die Stromversorgung des Trägersystems erfolgt mittels Lithium-Polymer-Akkumulatoren (LiPo) mit sechs in Reihe

geschalteten Zellen (6S). Bei einer Nennspannung der LiPo Zellen von $3,7\,\mathrm{V}$ ergibt sich eine Nennspannung des Akkus von $22,2\,\mathrm{V}$. Die Akkus sind über eine Stromverteilerplatine mit den ESCs verbunden. Die Flugsteuerung benötigt, wie viele andere Komponenten des Systems, eine niedrigere Spannung von $5\,\mathrm{V}$, die durch den zugehörigen Spannungswandler (PMU) bereitgestellt wird. Über diesen Pixhawk-eigenen Spannungswandler erfolgt zudem eine Spannungsmessung, die zum Auslösen eines Failsafe-Modus genutzt werden kann.
Ergänzt wird die Basissystem durch einen externen USB-Anschluss und eine Telemetrie-Verbindung zur Datenübertragung bei Konfiguration und Flug.

B. Zusatz für Autonomie

Aufbauend auf dem Basiskopter wird das System durch den Einsatz der EMQ-Steuerung für Aufgaben wie Navigation, Kollisionsvermeidung und intelligente Autonomie-Funktionen ergänzt. Die EMQ-Steuerung dient zur Kommandierung anderer Multikopter-Flugsteuerungen (hier Pixhawk 6X). Der zentrale Knotenpunkt für diese Zusatzsysteme ist eine Verteilerplatine (LD-Mainboard). Das LD-Mainboard verfügt über einen eigenen Mikrocontroller (EQCM). Mit Hilfe dieses Mikrocontrollers kann auf Basis verschiedener Sensordaten und Systemzustände das eingehende SBUS-Signal modifiziert und an die Flugsteuerung weitergegeben werden.
Weiterhin können über die EMQ-Steuerung zusätzliche Funktionen und periphere Systeme angesteuert werden. Das Ansteuern eines Servomotors ermöglicht beispielsweise das Lösen der mechanischen Verbindung zwischen Trägersystem und Messsonde.
Durch integrierte Sicherheitsmechanismen können jederzeit (z.B. im Fehlerfall) sämtliche Zusatzfunktionen deaktiviert werden. Der Fallback der EMQ-Steuerung bewirkt deren elektrische Brückung (Out of Loop) im Fehlerfall. Diese Architektur ermöglicht die Entwicklung und Erprobung möglicherweise kritischer, neu entwickelter Softwarekomponenten mit erhöhter Sicherheit.
Zur Redundanz sind auf dem LD-Mainboard zusätzlich eine inertiale Messeinheit und ein Barometer (BMO 280) untergebracht. Außerdem sind ein Here2-Modul und ein optischer Entfernungsmesser (Garmin LIDAR-Lite V3) direkt mit dem LD-Mainboard verbunden. Das Here2 stellt ein GPS-Signal über UART und ein Kompasssignal über I²C zur Verfügung. Zudem ist ein Punktlaser (Garmin LIDAR-Lite V3) nach unten ausgerichtet, der zur Messung der Höhe über Grund, bis zu einer Höhe von 40 Metern, dient. Eine Telemetrie-Schnittstelle ermöglicht die Übertragung von Daten der EMQ-Steuerung im Flug. Ein Interface-Board mit LEDs zur Anzeige des Systemzustands sowie möglicher Fehler bei der System-Initialisierung oder bei Vorflug-Checks und Tastern zum Reset bzw. Vorbereiten des Microcontrollers zum Flashen erweitert die Basisdrohne. Für die einfachere Zugänglichkeit kann der EQCM über eine externe USB-Schnittstelle programmiert werden.

Für die ressourcenintensive Echtzeit-Verarbeitung der Sensordaten wird das Basissystem mit einem Onboard-PC erweitert. Zum Einsatz kommt hier ein Brix mit i7-Prozessor, der über einen eigenen Spannungswandler mit $19,5\,\mathrm{V}$ versorgt wird. Für die Leitungsdetektion wird ein Quanergy M8-Lidar eingesetzt. Durch die extrem hohe Winkel-Auflösung von $0.03°$ erfüllt der Lidar den Anspruch mehrerer Messpunkte pro Scanlinie auf der Freileitung. Auf diese Weise wird die autonome Leitungsdetektion deutlich stabiler und zuverlässiger. Die Stromversorgung des Lidars erfolgt über einen Spannungswandler mit $24\,\mathrm{V}$ Ausgangsspannung.
Die Erweiterung um eine Eken 4K-Kamera ermöglicht dem Operator die Überwachung und Steuerung des Flugs aus der Sicht des UAS. Die Übertragung des Video-Streams erfolgt über ein Herelink-Modul.

III. Regelungskonzepte zur Positions- und Trajektorienregelung

In diesem Abschnitt folgt die Beschreibung möglicher Regelungskonzepte für die Flugplattform. Es werden drei Ansätze in Betracht gezogen. Derzeit wird an der Umsetzung dieser drei im folgenden vorgestellten Regler in einer Simulationsumgebung gearbeitet. Eine vergleichende Validierung durch Realversuche ist ebenfalls geplant.

A. PID - Regler

Als erstes wurde der PID-Regler aus der PX4-Steuerung für diesen Vergleich ausgewählt. Dieser spezifische Regler wird auf [8] vorgestellt und ist schematisch in Fig. 2 dargestellt. Es wurde sich für diesen Regler entschieden, da dieser Teil der PX4 Software ist, welche in den meisten handelsüblichen UAS verwendet wird und auch in diesem Projekt zum Einsatz kommt. Damit stellt dieser PID-Regler den industriellen Standard und eine gute Basis für die Evaluation der zwei weiteren Ansätze dar.

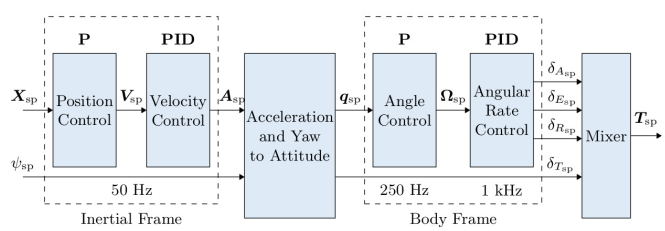


ABBILDUNG 2. Schema des PX4-Flugcontrollers. [8]

Der Vorteil der PID-Regelung an sich ist dabei die Schlichtheit, welche einen schnellen und stabilen Reglerentwurf erlaubt. Dazu kommt dass PID-Regler in den meisten Regelungen Anwendung finden, weshalb das Wissen über diese Technologie, ihre Vor- und Nachteile sowie ihre Grenzen bestens erforscht sind.
In diesem spezifischen Fall ist der PID als kaskadierter

Regler implementiert. Dabei ist vor allen Dingen die Trennung zwischen der Bewegung im Raum (Positions- und Geschwindigkeitsregelung) und der Drehung im Raum (Lage- und Winkelgeschwindigkeitsregelung) zu betonen. Diese ist eine Folge davon, wie sich das System fortbewegt. Ein Multikopter erzeugt mit seinen Rotoren einen Schub orthogonal zur Ebene in der sie angeordnet sind. Dies bedeutet, äußere Kräfte außer Acht lassend, dass ein Multikopter sich ausschließlich in Schubrichtung bewegen kann. Um eine Bewegung im dreidimensionalen Raum zu ermöglichen muss folglich die Schubrichtung angepasst werden. Dies wird durch die Lageregelung erreicht.

Da die Bewegung im Raum abhängig davon ist, dass die korrekte Lage eingeregelt ist, wird dieser Regelkreis, wie ABBILDUNG 2 zeigt, schneller ausgeführt. Die Frequenz für die Lageregelung beträgt 250 Hz während die Positions- und Geschwindigkeitsregelung mit 50 Hz arbeitet. Aus dem selben Grund erhöht sich die Frequenz von Lageregelung zu Winkelgeschwindigkeitsregelung noch einmal von 250 Hz zu 1 kHz.

Wie bereits erwähnt, ist das Funktionsprinzip des PID-Reglers vergleichsweise einfach. Zuerst wird ein Zielpositionsvektor $\mathbf{X}_{sp}$ mit einem P-Regler zu einen Zielgeschwindikeitsvektor $\mathbf{V}_{sp}$ umgerechnet. Dieser wiederum wird im nachfolgenden PID-Regler zu einem Zielbeschleunigungsvektor $\mathbf{A}_{sp}$. Diese Berechnungen finden alle im Initialsystem (Inertial Frame) statt. Im nächsten Schritt werden der Zielbeschleunigungsvektor und eine Zielausrichtung Ψ_{sp} in eine, als Quaternion angegebene, Solllage $\mathbf{q}_{sp}$ und die Änderung der Schubkraft ${}_{\delta}T_{sp}$ übersetzt. Ab hier finden die Berechnungen in Körpersystem statt.

Ein P-Regler berechnet dann aus der Solllage den Sollwinkelgeschwindigkeitsvektor $\mathbf{\Omega}_{sp}$. In der innersten Schleife berechnet schließlich ein PID-Regler aus dem Sollwinkelgeschwindigkeisvektor die Änderungen in Roll ${}_{\delta}A_{sp}$, Pitch ${}_{\delta}E_{sp}$ und Yaw ${}_{\delta}R_{sp}$. Alle Änderungen ${}_{\delta}A_{sp}$, ${}_{\delta}E_{sp}$, ${}_{\delta}R_{sp}$ und ${}_{\delta}T_{sp}$ werden dann in einem Mixer zu einem Vektor der Stellsignale T_{sp} zusammengefasst und an die Motoransteuerung übergeben.

B. *Energiebasierter Ansatz*

Als zweiter möglicher Regler wurde ein energiebasierten Ansatz nach [4] gewählt. Dieser scheint für das Projekt besonders geeignet, weil er eine optimale Trajektorienverfolgung bei vergleichsweise geringem Rechenaufwand ermöglicht. Ein weiterer Vorteil der energiebasierten Regelung ist die Koordinatenunabhängigkeit bei den Berechnungen. Zudem liefert das Verfahren einen Kandidaten für eine Lyapunov-Funktion, was den Stabilitätsnachweis vereinfacht. Weiterhin ist dieser Ansatz auf nahezu dem gesamtem Raum asymptotisch stabil ist. Die einzige Ausnahme ist hier, wenn das UAS auf dem Kopf steht. Dies ist bei der avisierten Anwendung nicht vorgesehen. Der Aufbau ist schematisch in ABBILDUNG 3 dargestellt.

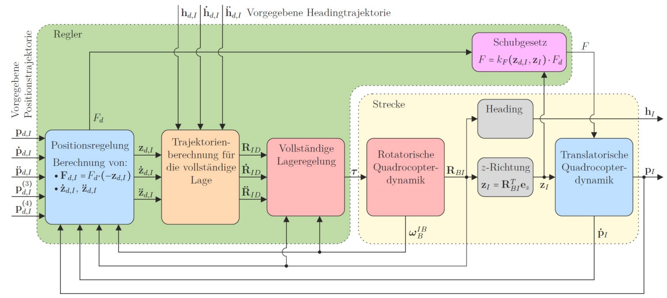


ABBILDUNG 3. Strukturbild des energiebasierten Reglers. [4]

Die Strecke, auf die sich der Regler dabei bezieht, ist folgendes mathematisches Modell des Flugverhaltens:

$$m\ddot{\mathbf{p}}_I = -\mathbf{D}\dot{\mathbf{p}}_I + mg\mathbf{e}_z - F\mathbf{z}_I \quad (1)$$

$$\dot{\mathbf{R}}_{BI} = -\langle\langle \boldsymbol{\omega}_B^{IB} \rangle\rangle \mathbf{R}_{BI} \quad (2)$$

$$\mathbf{J}\dot{\boldsymbol{\omega}}_B^{IB} = \langle\langle \mathbf{J}\boldsymbol{\omega}_B^{IB} \rangle\rangle \boldsymbol{\omega}_B^{IB} + \boldsymbol{\tau} \quad , \quad (3)$$

wobei $\mathbf{p}$ die Position des Kopters, $\mathbf{D}$ seine Dämpfungsmatrix, mg seine Gewichtskraft, $\mathbf{e}_z$ den Vektor $\begin{bmatrix}0 & 0 & 1\end{bmatrix}^\top$, F die Schubkraft, $\mathbf{z}_I$ den Vektor $\mathbf{e}_z$ transformiert aus dem Körpersystem ins Inertialsystem, $\mathbf{R}_{BI}$ die Lage als Rotationsmatrix, $\boldsymbol{\omega}_B^{IB}$ die Winkelgeschwindigkeiten des Kopters im Körpersystem, $\mathbf{J}$ die Trägheit und $\boldsymbol{\tau}$ die Stellmomente darstellen. Die rotatorische Quadrokopterdynamik repräsentieren dabei die Gleichungen (2) und (3), die transalatorische Quadrocopterdynamik findet sich in Gleichung (1).

Der Regler selbst wiederum ist ebenfalls vergleichsweise einfach strukturiert. Aus der aktuellen Sollposition und ihren vier Ableitungen der vorgegebenen Positionstrajektorie berechnet der Regler mithilfe des Eingangs erwähnten energiebasierten Ansatzes (für eine genauere Erläuterung siehe [3] und [5]) eine gewünschte Schubkraft F_{d} und eine Solllage der z-Achse des Körpersystems im Inertialsystem $\mathbf{z}_{\mathrm{d,I}}$, sowie die erste und zweite Ableitung der Selben. Die gewünschte Schubkraft wird dann nach dem so genannten Schubgesetz auf die Strecke angewendet, wobei k_F einen vom Lagefehler abhängigen Faktor darstellt.

Bei der Trajektorienberechnung für die vollständige Lage handelt es sich um eine Fusion von $\mathbf{z}_{\mathrm{d,I}}$ und der gewünschten Ausrichtung (Sollheading) $\mathbf{h}_{\mathrm{d,I}}$ in eine Solllage $\mathbf{R}_{ID}$ in Form einer Rotationsmatrix. Gleiches gilt für die jeweiligen ersten und zweiten Ableitungen. Abschließend berechnet die vollständige Lageregelung aus den Solllagen die benötigten Stellmomente, welche wiederum an die Motoransteuerung übergeben werden.

C. *Modellprädiktiver Regler*

Als dritte Variante wurde ein modellprädiktiver Regler (MPC) als vielversprechender Regler in den Vergleich aufgenommen. MPCs im allgemeinen sind dafür bekannt, Trajektorien sehr genau folgen zu können, da sie bei der Berechnung aktueller Stellgrößen zukünftige Verläufe berücksichtigen können. Die Funktionsweise eines MPCs ist in Fig. 4 dargestellt. Ein MPC funktioniert derart, dass auf Basis eines

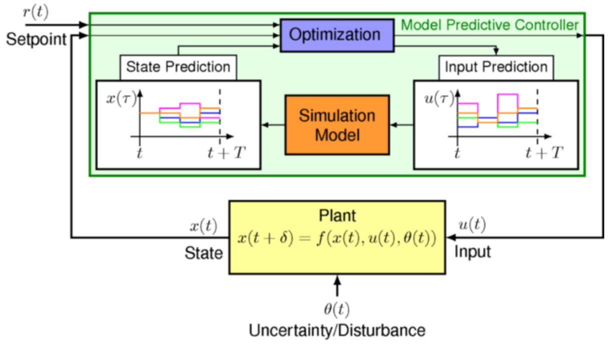


ABBILDUNG 4. Funktionsschema eines MPC. [1]

Referenzsignales $r(t)$ und des aktuellen Zustandes $x(t)$ des Systems (Plant) ein Optimierer den best möglichen Stellwert $u(t)$ berechnet. Diese Optimierung erstellt eine mögliches Stellsignal (Input Prediction) und simuliert auf Basis eines Modells (Simulation Model) das daraus folgende Verhalten des Systems (State Prediction). Der Optimierer verändert das potentielle Stellsignal so lange, bis das prädizierte Systemverhalten dem gewünschten Verlauf am nächsten kommt. Ist die Optimierung abgeschlossen, wird der erste Stellwert des Stellsignals an das reale System übertragen.

Ein Nachteil bei MPCs ist es, dass die Optimierung hohe Ansprüche an die Hardware und das für die Simulation verwendete dynamische Modell stellt. Dies resultiert in einem erhöhten Preis und/oder Gewicht, um die Berechnungen in Echtzeit sicherstellen zu können. Des Weiteren ist die Modellbildung sehr aufwendig, insbesondere weil viele relevante Parameter wie beispielsweise die Kennlinie zwischen Schub und Motorspannung messtechnisch erfasst werden müssen.

Die Autoren von [9] haben erfolgreich einen MPC auf eine reale Drohne angewendet. Dabei haben sie nur open source Software und Hardware verwendet, welche auch im Labor der Professur für Regelungstechnik zur Verfügung steht. Daher wird dieser spezifische MPC für den Vergleich genutzt. Folgende Gleichungen sind hierbei relevant:

$$_W\dot{\mathbf{r}}_B = {_W\mathbf{v}_B} \tag{4}$$

$$\dot{\mathbf{q}}_{WB} = \frac{1}{2}\mathbf{\Omega}(_B\boldsymbol{\omega})\mathbf{q}_{WB} \tag{5}$$

$$_W\dot{\mathbf{v}}_B = \frac{1}{m}\mathbf{C}_{WB\,B}\mathbf{T} + {_W\mathbf{g}} \tag{6}$$

$$_B\dot{\boldsymbol{\omega}} = \mathbf{J}^{-1}(_B\mathbf{M} - {_B\boldsymbol{\omega}} \times \mathbf{J}_B\boldsymbol{\omega}) \tag{7}$$

$$\mathbf{\Omega}(_B\boldsymbol{\omega}) = \begin{bmatrix} _B\boldsymbol{\omega}^{\times} & _B\boldsymbol{\omega} \\ -_B\boldsymbol{\omega}^{\top} & 0 \end{bmatrix}, \tag{8}$$

wobei $\mathbf{r}$ die Position, $\mathbf{v}$ die Geschwindigkeit, $\mathbf{q}$ die Lage als Quaternion, $\mathbf{C}$ die Lage als Rotationsmatrix, $\mathbf{T}$ die Schubkraft, $\mathbf{g}$ die Gewichtskraft, $\mathbf{J}$ die Trägheit, $\mathbf{M}$ das Stellmoment und $\boldsymbol{\omega}$ die Winkelgeschwindigkeit der Drohne darstellen. Des Weiteren ist die verwendete Software die Control Toolbox der ETH Zürich, welche mit einem Gauß-Newton-Multiple-Shooting (GNMS) Algorithmus arbeitet, um Multithreading zu ermöglichen.

D. *Prozesskette*

Um die im Rahmen dieses Kapitels vorgestellten Regler vergleichend zu testen, ist eine einheitliche Testumgebung bereitzustellen. Die praktische Umsetzung der hierfür avisierten Prozesskette für Simulation und Realversuche ist schematisch in ABBILDUNG 5 dargestellt.

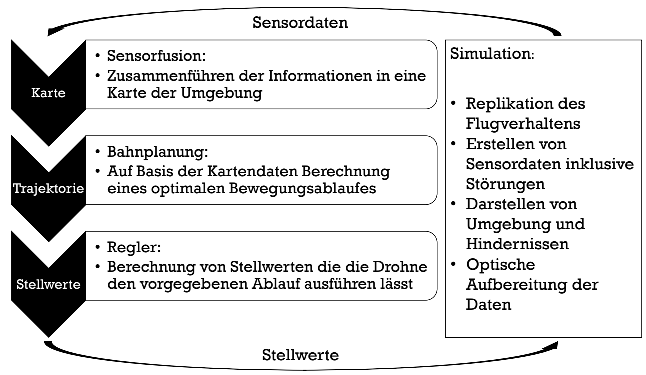


ABBILDUNG 5. Schema des Versuchsaufbaus

Wie in ABBILDUNG 5 zu sehen, sollen von der Simulation generierte Sensordaten fusioniert und basierend darauf eine einheitliche Karte der Umgebung erstellt werden. Auf Basis dieser Karte und der dort enthaltenen Informationen, wie Position und Lage der Drohne oder Entfernung von Hindernissen, soll eine Trajektorie berechnet werden, welche das optimalen Flugmanöver zur Erfüllung der Aufgabe wiedergibt. Die so erhaltene Trajektorie soll dann von der Flugregelung (Flightcontroller) in Stellwerte übertragen werden, welche die Drohne zum Abfliegen derselben braucht. In der Simulation sollen dann diese Stellwerte genutzt werden, um ein möglichst reales Flugverhalten in Echtzeit zu replizieren. Dabei werden auch die eingangs bereits erwähnten Sensordaten innerhalb der Simulation generiert. Dieser Aufbau hat den Vorteil, dass bei fehlerhaftem Verhalten einer Komponente ein Absturz nur simuliert wird, anstatt einen echten Absturz des Systems zu riskieren. Ist ein sicheres Betreiben der in der Simulation getesteten Software gewährleistet, soll diese in einem nächsten Schritt auf einen Testkopter angewendet werden.

Ein weiterer Vorteil dieses Aufbaus ist dabei, dass beim Wechsel auf das reale System lediglich die künstlichen Sensordaten durch echte ersetzt werden und der virtuelle Eingang der Stellwerte durch den physikalischen ersetzt wird. Final soll dann ein Prototyp mithilfe der an dem obig beschriebenen Schema validierten Software einen vorerst unbestromten Freileiter anfliegen und dort den Sensor absetzen.

IV. Erfassung elektrischer Grössen auf Freileitungen im Mittel- und Hochspannungsnetz

In diesem Abschnitt wird auf die Untersuchungen zur Konzeptionierung und Entwicklung einer geeigneten Methodik zur Messung elektrischer Größen auf Freileitungen eingegangen. Eine direkte Einbindung von Stromsensoren in den Stromkreis und ein direkter Anschluss von Spannungssensoren an die Leiter ist auf Freileitungen im Mittel- und Hochspannungsnetz nicht möglich. Daher besteht die große Herausforderung darin, Netzparameter indirekt über die Feldverhältnisse zu ermitteln. Das Ziel ist, im Rahmen dieses Projektes ist zunächst die Ausarbeitung eines Anforderungskataloges für ein Messsonde zum Einsatz auf Freileitungen. Dieser soll insbesondere die Parameter Gewicht und Geometrie umfassen, sowie unter Umständen weitere erforderliche bauliche Parameter. Aufgrund der Zielsetzung, die Messsonde mit Hilfe eines UAS auf Freileitungen im Mittel- und Hochspannungsnetz abzusetzen, sind deren Gewicht und Größe gewisse Grenzen gesetzt. So darf beispielsweise die Masse der Messsonde das Freileitungsseil nicht übermäßig belasten und das abzusetzende Messsystem muss von einem UAS getragen werden können, welches aufgrund seiner möglichst geringen Abmessungen auch innen liegende Leiterseile ohne Gefahr von Kollisionen erreichen kann.

Messung der elektrischen und magnetischen Felder

Im Allgemeinen sind Feldsensoren aufgrund ihrer Anfälligkeit gegenüber Störungen durch äußere Einflüsse und ihrer teilweise massiven Struktur in ihren Anwendungen eingeschränkt. Dies kann beispielsweise dazu führen, dass sie den zeitlichen Verlauf von elektrischen und magnetischen Wechselfeldern nicht oder nur unzureichend genau ermitteln können. Zudem stellen die Begrenzungen für Größe und Gewicht der Messsonde in diesem Fall eine besonderen Herausforderung für die Entwicklung von Sensoren mit ausreichender Genauigkeit dar. Weiteren Herausforderungen ergeben sich aus Formvorgaben, welche aus der Entwicklung einer geeigneten Absetzvorrichtung entstehen können.

Unter den elektrischen Feldsensoren (E-Feld-Sensoren), bilden die sogenannten faseroptischen elektrischen Feldsensoren eine Ausnahme bezüglich der Empfindlichkeit gegenüber Störungen. Mit diesen kann daher ein Teil der oben genannten Problemstellungen, welche bei klassischen Messsystemen bestehen, gelöst werden. Faseroptische E-Feld-Sensoren basieren auf dem linearen elektrooptischen Effekt, welcher auch als Pockels-Effekt bekannt ist. Dieser beschreibt, wie sich die Lichtausbreitungseigenschaften (z.B. der Brechungsindex) eines Kristalls verändern, wenn er sich in der Umgebung eines elektrischen Feldes befindet [10]. Eine stark vereinfachte Visualisierung des Aufbaus eines Sensors, welcher auf dem Pockels-Effekt basiert, ist in Abbildung 6 dargestellt. Die Polarisation des Lichtes wird im elektrooptischen Material durch Anlegen eines elektrischen Feldes so beeinflusst, dass das Verhältnis der Lichtintensitäten zwischen Ein- und

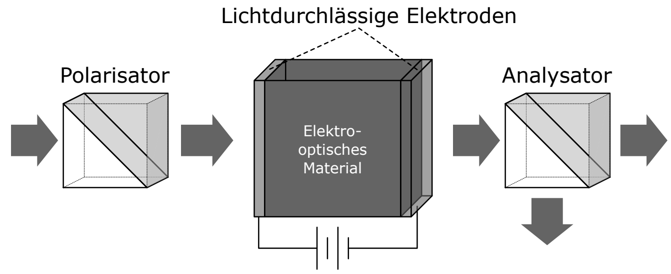


Abbildung 6. Prinzipieller Aufbau eines Sensors, welcher auf dem Pockels-Effekt beruht nach [11].

Ausgang von der Höhe des elektrischen Feldes abhängt [11]. Es ist jedoch eine spezielle Auswerteeinheit nötig, um von den Lichtintensitäten auf die tatsächliche Feldstärke zu schließen. Trotz der aufwendigen Bauweise dieser Sensoren bieten Sie für das beschriebene Vorhaben eine Reihe von Vorteilen:

- Geringe Größe und geringes Gewicht
- Hohe Empfindlichkeit
- Hohe Messgenauigkeit
- Große Bandbreite
- Hohe Schadensschwelle.

Tabelle I
Technische Spezifikationen von fiberoptischen E-Feld-Sensoren.

Parameter	***Wert***
Frequenzbereich	$0 - 20\,\mathrm{GHz}$
Empfindlichkeit	$10\,\mathrm{mV/m} - \mathrm{Hz}^{\frac{1}{2}}$
Max. E-Feld	$> 5\,\mathrm{MV/m}$
Größe	8 mm x 50 mm
Max. messbares E-Feld	$200\,\mathrm{MV/m}$

Tabelle I zeigt beispielhaft die Spezifikationen für einen faseroptischen E-Feld-Sensor von der Firma Agiltron Inc. Hieran ist zu sehen, dass es im Bereich faseroptischer Sensoren auch sehr kleine Ausführungen gibt. Im Rahmen von Messungen im Hochspannungslabor sowie mit Hilfe von Simulation der Feldverhältnisse an Freileitungen werden aktuell die genauen Anforderungen für die Sensoren abgeleitet. Um später tatsächlich eine Messsonde auf einer Freileitung absetzen zu können, müssen einige weitere Voraussetzungen erfüllt sein. Am Lehrstuhl für Elektrische Energiesysteme wird daher auch an den folgenden Punkten geforscht:

- Entwicklung einer Messsonde bzw. deren Gehäuse, welches ein Anbringen und Lösen von der Freileitung ermöglicht und idealerweise keinen Einfluss auf die zu messenden elektromagnetischen Felder selbst hat
- Analyse von möglichen Gegenmaßnahmen zur Reduzierung von Einflüssen elektromagnetischer Felder auf die

Messungen
- Bewertung der Eigenschaften verschiedener Sensortypen in Bezug auf Positionierung und Genauigkeit, um aus den gemessenen Feldverhältnissen Rückschlüsse auf die Strom- und Spannungsverhältnisse zu ziehen

V. Zusammenfassung und Ausblick

Dieses Paper stellt die Lösungsansätze für die zentralen Herausforderungen im Rahmen des Projekts *Digitalisierte, rechtssichere und emissionsarme flugmobile Inspektion und Netzdatenerfassung mit automatisierten Drohnen (kurz DNeD)* dar. Ziel des Projekts ist die Erforschung und Erprobung eines intelligenten flugfähigen Systems, welches automatisiert Freileitungen inspiziert und dabei befähigt ist, einen Sensor zur Erfassung elektrischer Größen im Mittel- und Hochspannungsnetz auf einer Freileitung abzusetzen.

Der Aufbau des Papers ist an die drei zentralen Handlungsfelder des Projekts angelehnt. Nach einer allgemeinen Einführung wurde zunächst das Hardwaredesign des avisierten Kopters vorgestellt. Die Ausführungen zeigen, dass ein Hexakopter verwendet werden soll, um eine Redundanz bei den Antriebskomponenten zu haben. Die benötigte Bordelektronik und Sensorik verfügt ebenfalls über eine hinreichende Redundanz. Somit kann bei Auftreten von im Multikopterbetrieb gängigen Störungen ein sicherer Betrieb gewährleistet werden. Die vorgestellten Schnittstellen in Hard- und Software berücksichtigen alle erforderlichen Eingriffsmöglichkeiten.

Der Fokus in Kapitel III liegt auf der Positions- und Trajektorienregelung des einzusetzenden UAS. Es werden drei verschiedene Reglerstrukturen vorgestellt, die im weiteren Verlauf des Projekts sowohl durch Simulationen als auch durch Realversuche vergleichend validiert werden sollen. Die dafür avisierte Prozesskette ist ebenfalls Teil der Ausführungen. Ergebnisse zur Bewertung der vorgestellten Regler konnten noch nicht präsentiert werden. Dies wird Teil folgender Veröffentlichungen sein.

In Kapitel IV werden schließlich die Herausforderung für den Aufbau der abzusetzenden Messsonde und entsprechende Lösungsansätze beschrieben. Zentrales Element ist hier das Messprinzip von faseroptischen elektrischen Feldsensoren, welches eine kontaktlose Messung elektrischer Größen ermöglicht. Auch die Anforderungen an möglichst geringes Gewicht und Größe werden durch solche Sensoren erfüllt. Auch in diesem Themenbereich liegen noch keine Validierungsergebnisse vor, da die Hardware noch in Beschaffung ist. Somit wird die Darstellung praktischer Messungen ebenfalls Teil weiterer Veröffentlichungen sein.

Aktuell befinden sich viele der vorgestellten Komponenten sowohl für den Kopter als auch für die Messsonde in Beschaffung. Sobald diese abgeschlossen ist, werden entsprechende Validierungen durchgeführt, um basierend auf den Ergebnissen ggf. noch konzeptionelle Anpassungen vor Beginn des Aufbaus eines Funktionsmusters vornehmen zu können.

Danksagung

Das Projekt Digitalisierte flugmobile Netzdatenerfassung mit automatisierten Drohnen (DNeD) wird durch dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr gefördert. Die Autoren bedanken sich für die Förderung.

Literatur

[1] F. Allgöwer, “Model Predictive Control,” Institute for Systems Theory and Automatic Control, Universität Stuttgart, https://www.ist.uni-stuttgart.de/research/group-of-frank-allgoewer/model-predictive-control, Stuttgart, Deutschland, letzter Aufruf September 2022.

[2] J. A. Birchbauer, A. Einfalt, G. Komar, O. Pischler, U. Schichler und S. Frank, “Voltair - Das Unsichtbare sichtbar machen,” Energieforschungsprogramm , 4. Ausschreibung, Projektnummer 865003, Endbericht, Österreich, Juli 2020.

[3] F. Bullo and A. D. Lewis, “Geometric control of mechanical systems: modeling, analysis, and design for simple mechanical control systems,” 49th volume, Springer, 2019.

[4] O. Fritsch, “Energiebasierte Lage- und Positionsfolgeregelung für einen Quadrocopter,” München: TECHNISCHE UNIVERSITÄT MÜNCHEN, 2014.

[5] M. G. C. Grunewald,“Energiebasierte Regelung von Fahrzeugkolonnen in der Ebene,” Aachen: RWTH-Aachen, Deutschland, 2011.

[6] M. Beiro, “The Linebird Osprey Non-conductive Payload System (NPS),” https://linebird.net/, Richmond, USA, letzter Aufruf September 2022.

[7] N. N., “T-Motor MN505-S KV320,” Produktinformation, https://store.tmotor.com/goods.php?id=698, Nanchang, China, letzter Aufruf September 2022.

[8] N. N., “PX4-Flugsteuerung,” Produktinformation, https://docs.px4.io/v1.12/en/concept/architecture.html, letzter Aufruf September 2022.

[9] D. Tzoumanikas, Q. Yan and S. Leutenegger, “Nonlinear MPC with Motor Failure Identification and Recovery for Safe and Aggressive Multicopter Flight,” IEEE International Conference on Robotics and Automation (ICRA), Paris, Frankreich, 2020.

[10] B. He, S. Liu , P. Zhu, Y. Li and D. Cu, “The working characteristics of electric field measurement based on the Pockels effect for AC–DC hybrid fields”, Measurement Science and Technology, Volume 29, Number 12, IOP Publishing Ltd., October, 2018, DOI: https://doi.org/10.1088/1361-6501/ aae4c8.

[11] A. Kumada and K. Hidaka “Directly High-Voltage Measuring System Based on Pockels Effect”, IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 28, NO. 3, JULY 2013, DOI: https://doi.org/10.1109/TPWRD.2013.2250315.

CNN based Drone Detection in Infrared Images

Purbaditya Bhattacharya, Patrick Nowak, Daniel Ahlers, Martin Holters, Udo Zölzer
Department of Signal Processing and Communication
Helmut Schmidt University
Hamburg, Germany
firstname.lastname@hsu-hh.de

***Abstract*—Methods based on convolutional neural networks (CNNs) for drone detection in infrared images are explored in this paper. For the task of drone detection, a dataset of infrared images containing drones is initially built from a publicly available database and drone videos captured with our cameras. The required drone images are extracted and manually labelled with the help of an image labelling tool. Multiple configurations of popular pretrained CNN models including EfficientDet and Yolo are subsequently trained on the combined dataset. The trained models are employed on the test dataset and their performance is evaluated.**

***Index Terms*—drone detection, object detection, CNN, image processing, dataset, EfficientDet, Yolo v5**

I. Introduction

Unmanned aerial vehicles (UAV) or drones have seen a rapid growth in popularity in recent years. While drones were initially adopted and used in military operations, primarily for surveillance, communication, and transportation, they are now widely used in industrial and commercial applications. Some of the use cases include surveillance for law enforcement, monitoring of regions for emergency and rescue operations, transportation, aerial photography, and recreational activities. Given their abundance and gradual increment in usage, public safety or security becomes an area of concern and must be paid an attention to. Hence, reliable and robust methods should be developed in order to detect and track drones to monitor their activities. An automated drone detection system can generate an alert based on any anomalous activity. Such systems can operate based on images captured in the visible or infrared range. In this context, infrared images can provide better visibility under certain conditions where the background is noisy or cluttered and the environmental illumination is low. Recent methods for object detection include the usage of CNNs which usually provide a very high accuracy in such kind of tasks [1]–[3]. In this work, the initial goal is to use a selection of such network models in order to detect drones in infrared images.

This work is part of the dtec.bw project "Digital Sensor-2-Cloud Campus-Platform" (DS2CCP), in which a 5G campus network is set up at Helmut Schmidt University. As can be seen in Figure 1, the 5G campus network is used to connect camera and processing computer. In the uplink, image data is sent from the camera to the processing computer in order to perform the drone detection on a high-performance computer. In this way, image data from multiple cameras can be handled simultaneously on the same computer. Here, the

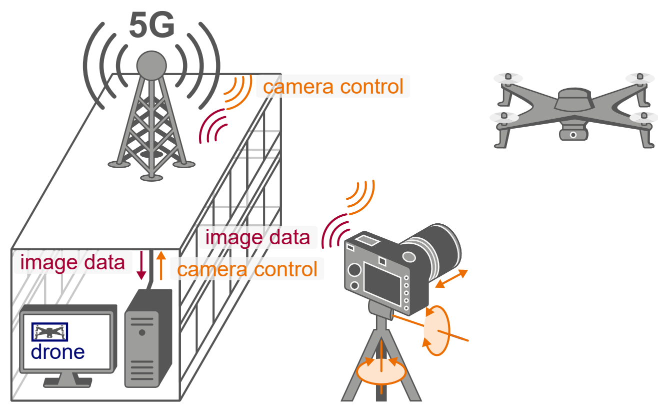


Figure 1. Communication between camera and processing computer via 5G campus network.

5G campus network should offer both high data rates and low latency. Furthermore, the downlink enables the transfer of camera control data, e.g. pan, tilt, and zoom, from the processing computer to the camera allowing flexibility in camera maneuvering and changes in the viewing area of the individual cameras.

II. Dataset

To train the network models for drone detection a suitable dataset of infrared images containing drones is required. A few infrared image drone datasets are publicly available from which a dataset [4] is selected which is a part of the ICCV drone detection challenge. The dataset contains 70 video files having 1000 frames each, and the drones fly across multiple backgrounds in the videos. Each video has a spatial resolution of 640×480 pixels and features a single drone, located approximately at the center of each frame. Although there are nearly 70000 images with drones, a large number of images have redundant or indiscernible content. The redundancy is primarily due to limited drone movement and uniform background in many videos. Hence, a small subset is selected for training. Apart from the public dataset, a dataset is constructed from drone videos captured using three different cameras. Firstly, a Sony Alpha 6000 camera equipped with a lens with a focal length of 16-50 mm is used to record drone videos in the visible spectrum with a resolution of 1920×1080 pixels. Secondly, a FLIR Scion OTM366 is used to record drone videos in the infrared spectrum with a resolution of 640×480 pixels. Finally, infrared videos with a higher resolution of

https://doi.org/10.24405/14543

FIGURE 2. ANNOTATED IMAGE CAPTURED BY FLIR SCION OTM366.

1024×768 pixels are recorded using an InfraTec VarioCAM HD Z equipped with a zoom lens (25-150 mm). The drone videos were recorded simultaneously with all three cameras on the football field of the Helmut Schmidt University from different perspectives and distances between 100 and 200 meters. In total, three different drones can be seen inside the videos. In most of the videos, the Artcopter Raptor drone is shown. The second drone in some videos is the Holybro X500. A third smaller drone is visible in some videos, which would be the DJI Mavic Pro 2.

TABLE I
TRAINING AND TEST DATASET

Dataset	**Public**	**FLIR**	**Total**
Train	6450	6983	13433
Test	0	1683	1683

In this work, only videos captured via the FLIR Scion OTM366 are used. In order to use these videos for training and evaluation purposes, drones inside the videos must be labeled. For this purpose, the LabelImg [5] graphical annotation tool is used. The annotations are done in the Pascal VOC [6] format which are transformed to YOLO and then to COCO format [7] according to the requirements of training. Presently, three videos containing a total of 21953 frames are being labeled, of which 12608 frames are already labelled and a fraction is used. In the future, videos recorded with the Sony Alpha 6000 and InfraTec VarioCAM HD Z will be labelled as well and a diverse dataset will be created. This dataset will also be expanded in the future. An annotated infrared image captured by FLIR Scion OTM366 containing multiple drones is shown in FIGURE 2.

The dataset prepared with images from FLIR Scion OTM366 is initially divided into easy and difficult images depending on the visibility of drones due to clutter or occlusion. In this work, the relatively easy images are selected where the drones are mostly visible. The final combined dataset contains 13433 images for training and 1683 images for testing, as shown in TABLE I.

III. NETWORK DESCRIPTION

To train a new dataset for detection task, CNNs that are pretrained on large datasets are usually preferred rather than a randomly initialized CNN. A pretrained network is generally able to converge much faster and achieve better performance compared to a network trained from scratch. Hence, the EfficientDet [8] and Yolo v5 [9] network models which are pretrained on a version of the Common Objects in Context (COCO) dataset [10], are lightly modified and used to train the final dataset for drone detection. The selected CNNs are two of the most popular networks for object detection and are therefore selected in this work. A minimal overview of the network architectures is provided in FIGURE 3 with processing blocks. The architectures of both models contain a backbone network, followed by a neck (feature network) and the classification and detection heads.

The backbone network is usually a pyramidal network where the feature maps are downscaled after a certain number of layers. The layers primarily include convolution, batch normalization, rectification, sigmoid linear unit or swish activation, and summation and / or concatenation layers. The EfficientDet architecture modifies the EfficientNet [11] backbone and downscales the feature maps gradually by a factor of 2 until an overall factor of 128. Hence, an input resolution of 640×640 is downscaled to a final resolution of 5×5. The architecture of Yolo v5 is also made of a pyramidal backbone, known as CSPDarknet53, and it downscales the feature maps gradually by a factor of 2 until an overall factor of 32. Therefore, an input resolution of 640×640 is downscaled to a final resolution of 20×20. The backbone of Yolo v5 contains many more layers compared to EfficientDet. Yolo v5 also has an additional spatial pyramid pooling layer (SPP) at the end of the backbone which applies multiresolution parallel pooling kernels and concatenates the generated feature maps.

In the neck, feature maps from multiple levels of the backbone, having multiple resolutions are initially processed by different layers and then combined via summation or concatenation. In order to combine certain feature maps, the lower resolution (LR) feature maps are upsampled by bilinear interpolation while the higher resolution (HR) feature maps are downsampled by convolution with stride. In EfficientDet, the neck contains multiple bidirectional feature pyramid network (BiFPN) structures which upsample the feature maps gradually by an overall factor of 16, and downsample them again while combining the features of similar resolution via summation. In Yolo v5, the processing in the neck is similar to EfficientDet but relatively simpler and is referred to as the path aggregation network (PAN). Additionally, the feature maps of similar resolutions within Yolo v5 are usually combined through concatenation.

The neck is usually followed by several classification and detection heads which are primarily formed by convolution, activation, and batch normalization layers. The heads originate

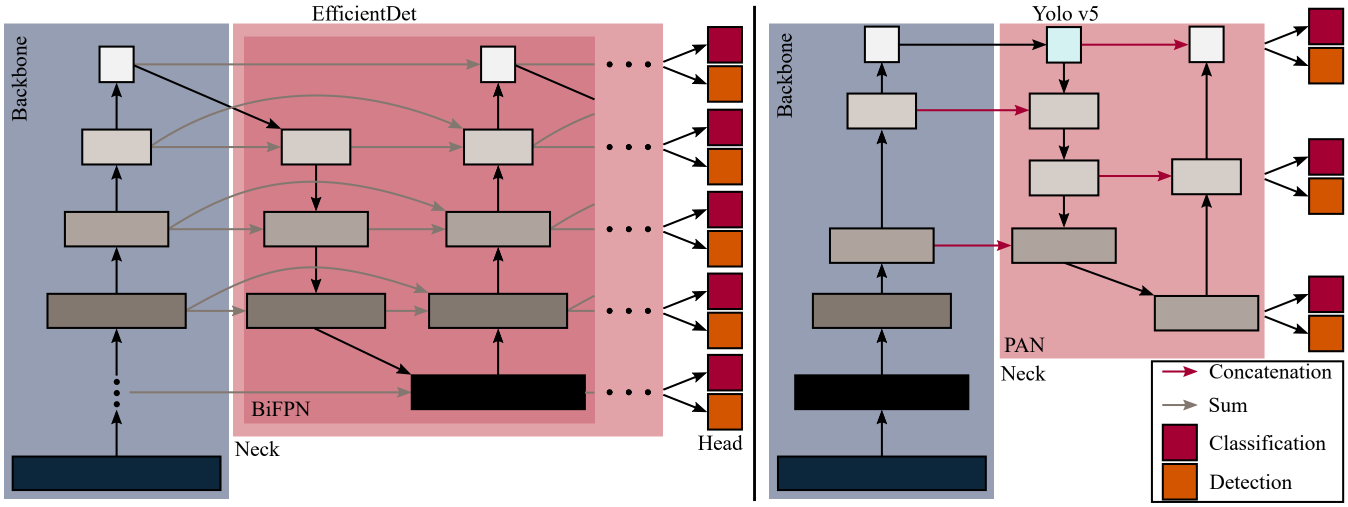


FIGURE 3. A MINIMAL OVERVIEW OF THE EFFIECIENTDET AND YOLO V5 NETWORKS.

from multiple levels of the last pyramid in the neck and have multiple sizes. The classification heads end with softmax layers to transform the values into probabilities. The feature maps at the end of each head are vectorized, reshaped, and concatenated to generate a final vector. The usual shape of this vector is $(4 + numclasses) \times numcandidates$, where numclasses denotes the number of classes, numcandidates denotes the total number of predictions or anchor boxes, and the bounding box refinements are predicted by 4 values in the form of [x, y, height, width], usually normalized. For Yolo v5 the shape of the output vector would be $(5+numclasses) \times numcandidates$ because of an additional metric computed in the loss layer. Given an input resolution of 640×640, the final vector size of EfficientDet is 5×76725 and the final vector size of Yolo v5 is 6×25200. It is noteworthy to mention that these networks are scalable and can be expanded or shrinked based on the input image dimensions or memory limitations during training. The scalability is normally achieved by adding or removing layer groups to or from the architecture and by varying feature map depths.

Both EfficientDet and Yolo v5 define anchor boxes of multiple sizes based on the possible object sizes in the datasets they are pretrained on. The anchor boxes are tiled across an entire image and usually serve as initial bounding box predictions. The positions of the anchor boxes are gradually updated during training. The predictions are processed in the loss layer. In EfficientDet, the layer contains the classification or focal loss, and the box regression loss functions which are given by

$$L_{\text{class}} = -\Sigma\alpha_c \cdot (1 - p_c)^\gamma \cdot y_c \log(p_c), \tag{1}$$

$$L_{\text{box}} = \begin{cases} \frac{1}{2\beta} \cdot (p_b - y_b)^2 & \text{if } |p_b - y_b| < \beta \\ |p_b - y_b| - \frac{\beta}{2} & \text{otherwise} \end{cases}, \tag{2}$$

where α_c and γ denote a data balancing and smoothing factor, respectively, β denotes a factor in smoothL1 loss, y_c denotes the ground truth class, p_c denotes the predicted class probability, y_b denotes the bounding box ground truth value, and p_b denotes the corresponding prediction of an object instance. The overall loss is averaged across all examples.

Similarly, Yolo v5 applies the focal loss function but the corresponding box loss function given by

$$L_{\text{box}} = 1 - \text{IOU}(y_b, p_b), \tag{3}$$

and an objectness loss approximately given by

$$L_{\text{obj}} = -\Sigma y_o \log(f(p_o)), \tag{4}$$

where $p_o = \text{IOU}(y_b, p_b)$, $f(\cdot)$ denotes a function, and IOU is the intersection over union between a ground truth and predicted bounding box, given by

$$\text{IOU} = \frac{p_b \cap y_b}{p_b \cup y_b}, \tag{5}$$

where $(p_b \cap y_b)$ is the intersection between the predicted and ground truth bounding boxes and $(p_b \cup y_b)$ denotes the union between them. The final loss is averaged across all examples. For a more detailed description of the network components, network scaling, definition of anchor boxes, model related pre-processing, etc., the original resources should be referred.

IV. TRAINING

The CNN models are trained in Pytorch on a Quadro RTX 8000 machine. In this work, the official implementation of Yolo v5 [9] and an unofficial Pytorch implementation [12] of EfficientDet is used. Pretrained models of the CNNs are finetuned instead of training a new model with randomly initialized parameters to achieve faster better results. The models need to be modified in order to accommodate a 2-class classification task. This results in a new layer or a replacement of weights in the last layer of the pretrained models, initialized randomly. Since the network models require square images, the training images are zero padded instead of resizing, since the natural aspect ratio of the captured objects is preserved. The coordinates of the bounding box labels are also adjusted accordingly. The labels for Yolo v5 are formatted as text data. Each image has a ground truth text file containing the object class identification number (ID) and the coordinates in the form of $[x_{\text{center}}, y_{\text{center}}, \text{width}, \text{height}]$, normalized by the image width and height, respectively. In case of multiple drones, there are multiple such annotations in the text file. The labels for the EfficientDet network are provided in a format used for COCO data. The label is a single .json file containing the relevant information about all the training or test images including image name, size, image ID, class name, class ID, coordinates, object area, and certain flags. The coordinates are presented in the form of $[x_{\text{corner}}, y_{\text{corner}}, \text{width}, \text{height}]$, normalized by the image width and height, respectively.

TABLE II provides a summary of the important information related to the training of both networks including the number of epochs, learning rate and related hyperparameters, batch size, optimization, and data augmentation methods used. The default augmentation method refers to translation, rotation, flipping, etc. Various model configurations having different sizes are also trained to review their performance during evaluation. Two variants of EfficientDet, EfficientDet-D0 and EfficientDet-D1, are trained where the earlier model is less complex than the latter in terms of parameters. Similarly, three versions of Yolo v5 denoted by nano (n), small (s), and medium (m) are trained and the nomenclature suggests an increasing order of complexity.

TABLE II
TRAINING DETAILS

	EfficientDet	**Yolo v5**
Number of epochs	100	100
Initial learning rate	1e-4	1e-2
Momentum	0.9, 0.999 (betas)	0.94
Weight decay	1e-3	5e-4
Batch size	16	16
Optimization	Adam, SGD	SGDM
Data augmentation	Mean subtraction, default augmentation	Default augmentation, mosaic input augmentation
Models trained	EfficientDet-D0, D1	Yolo v5-n,s,m

V. EVALUATION

To evaluate an object detection task various metrics related to a successful classification of an object and a successful detection of that object are used and combined in various ways to create more intuitive metrices. In the case of classification, an object is assigned with predicted confidence scores which denote its probabilities of belonging to multiple classes. When its highest score is above a pre-defined threshold the object is deemed to belong to the corresponding class. This prediction is compared with a label to determine its success or failure and thus generate a binary metric. In the case of detection, the intersection over union (IOU) metric is calculated which is given by Eq. (5). An IOU threshold provides a binary outcome in terms of success or failure.

A successful classification and detection results in a true positive (TP) example while an unsuccessful outcome results in a false positive (FP) or a false negative (FN) example. FP refers to detections that have no ground truth and FN refers to correct objects that are not detected. Based on these examples the precision (P) and recall (R) metrics are defined as

$$\mathrm{P} = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FP}}, \tag{6}$$

$$\mathrm{R} = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FN}}, \tag{7}$$

which can be further used to plot a precision-recall (PR) curve based on the outcome of all test examples. Finally, the average precision (AP) and the mean average precision (mAP) metrics are calculated from the PR curve.

FIGURE 4. EXAMPLE RESULT FROM EFFICIENTDET-D0.

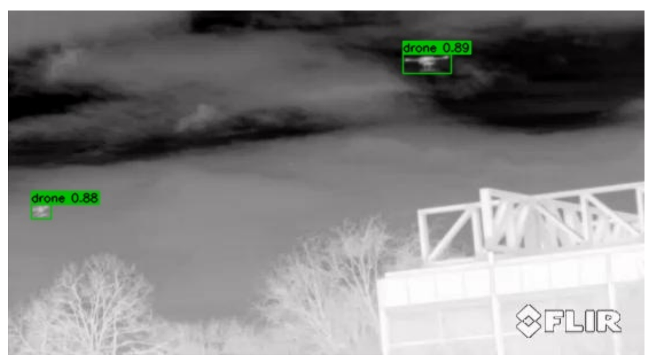


FIGURE 5. EXAMPLE RESULT FROM YOLO V5M.

In this work the evaluation is performed based on AP as defined by the COCO evaluation standard. One of the AP metrics is calculated based on an IOU threshold of 0.5. A second AP metric is also calculated based on increasing IOU thresholds from 0.5 to 0.95 with a step size of 0.05 and then calculating the average value. The AP value lies between 0 and 1 and a higher value indicates a better performance.

TABLE III provides the evaluation results of the five trained models on the test dataset in terms of the AP values, the number of model parameters, and model complexity in FLOPS. As

TABLE III
EVALUATION OF MODELS

Network Models	Number of parameters	Complexity (GFLOPS)	$AP_{IOU=0.5}$	$AP_{IOU=0.5:0.95}$
EfficientDet-D0	3828k	3.8	0.870	0.626
EfficientDet-D1	6555k	5.8	0.852	0.600
Yolo v5n	1761k	4.1	0.955	0.732
Yolo v5s	7013k	15.8	0.963	0.734
Yolo v5m	20853k	47.9	0.968	0.740

shown in the table, the models perform well on the test dataset. The Yolo v5 models perform particularly well with Yolo v5m producing the best AP values. The AP scores of EfficientDet-D0 and D1 are also quite good but lower than Yolo v5. This is primarily due to the failure of the EfficientDet models to detect smaller drones with correct bounding boxes in some images. In some images, multiple bounding boxes with same confidence scores might occur based on the choice of IOU threshold for non-maximum suppression (NMS), and the wrong bounding box is selected if the threshold is lowered. This might occur due to imprecise anchor box definition for the task or a lack of proper weighting in the loss function, and thus requires further investigation. FIGURE 4 shows an example detection result from EfficientDet-D1, where the smaller drone is not detected.

The Yolo v5 models perform admirably on the test images and can detect very small or distant drones as well. FIGURE 5 shows an example detection result from Yolo v5m, where the bounding box around the smaller drone is quite tight and has a high confidence score. Occasionally, the models are also able to detect drones from a relatively difficult background although they are not trained with any difficult examples.

In terms of computational complexity or parameters, the EfficientDet models are relatively small along with Yolo v5n, while the remaining models have a higher complexity. Based on the results on the current test dataset it can be concluded that Yolo v5n is a good model considering complexity and performance. A test run on the FLIR Scion OTM366 videos shows that it can achieve an average speed of 80 frames per second (FPS) on GPU.

VI. CONCLUSION

In this work, drone detection is performed on infrared images based on EfficientDet and Yolo v5 CNN models. The image dataset is created by combining a public and a custom dataset. Videos of flying drones are captured with multiple cameras and the images are extracted for annotation. The LabelImg tool is used to annotate the images captured by FLIR Scion OTM366 and create the custom dataset. A big fraction of the annotated images along with images from the public dataset are used for training and testing the models. The evaluation of the finetuned models on the test images indicates a good performance from the EfficientDet models and a very good performance from the Yolo v5 models.

In the future, the goal is to annotate the videos captured by all cameras, while continuing to capture more videos of drones in different surroundings. This should be followed by a statistical analysis and overview of the final dataset. While CNNs tend to improve quite rapidly, more recent and better models can be experimented with. Such models can be modified with additional CNN modules that usually improve object detection tasks. Recurrent models can be created or existing CNNs can be modified to be recurrent in nature and retrained on sequential images for improved detection and tracking. The comparatively difficult images where the drone is partially occluded or obscured due to background should also be integrated in the dataset to improve the performance and robustness of the models.

ACKNOWLEDGMENT

This project is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project “Digital Sensor-2-Cloud Campus-Platform” (DS2CCP)]. We would also like to thank the department of Electrical Measurement Engineering at Helmut Schmidt University for the opportunity of recording their drones during test flights on the football field.

REFERENCES

[1] J. Redmon, S. Divvala, R. Girshick and A. Farhadi, “You Only Look Once: Unified, Real-Time Object Detection,” in *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2016, pp. 779–788, doi: 10.1109/CVPR.2016.91 .

[2] R. Girshick, J. Donahue, T. Darrell and J. Malik, “Rich Feature Hierarchies for Accurate Object Detection and Semantic Segmentation,” in *2014 IEEE Conference on Computer Vision and Pattern Recognition*, 2014, pp. 580–587, doi: 10.1109/CVPR.2014.81 .

[3] W. Liu et al., “SSD: Single Shot MultiBox Detector,” In: Leibe, B., Matas, J., Sebe, N., Welling, M. (eds) *Computer Vision – ECCV 2016. ECCV, 2016. Lecture Notes in Computer Science*, vol. 9905. Springer, Cham. https://doi.org/10.1007/978-3-319-46448-0 _2.

[4] N. Jiang et al., “Anti-UAV: A Large Multi-Modal Benchmark for UAV Tracking,” in *ArXiv*, abs/2101.08466, 2021, [Online]. Available: https://github.com/ZhaoJ9014/Anti-UAV [Visited on 26. August 2022].

[5] Tzutalin, “LabelImg,” Free Software: MIT License, 2015, [Online], Available: https://github.com/heartexlabs/labelImg. [Visited on 26. August 2022].

[6] M. Everingham, L. Van Gool, C.K.I. Williams et al., “The Pascal Visual Object Classes (VOC) Challenge,” in *International Journal of Computer Vision*, vol. 88, pp. 303–338, 2010, https://doi.org/10.1007/s11263-009-0275-4, [Online], Available: http://host.robots.ox.ac.uk/pascal/VOC/ [Visited on 26. August 2022].

[7] T.Y. Kim, “Yolo-to-COCO format converter,” [Online], Available: https://github.com/Taeyoung96/Yolo-to-COCO-format-converter [Visited on 26. August 2022].

[8] M. Tan, R. Pang and Q.V. Le, “EfficientDet: Scalable and Efficient Object Detection,” in *2020 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, 2020, pp. 10778-10787, doi: 10.1109/CVPR42600.2020.01079 .

[9] G. Jocker et. al., “ultralytics/yolov5: v3.1 - Bug Fixes and Performance Improvements,” Zenodo, Oct 2010, https://doi.org/10.5281/zenodo . 4154370, [Online], Available: https://github.com/ultralytics/yolov5 [Visited on 26. August 2022].

[10] T.-Y. Lin et al., “Microsoft COCO: Common Objects in Context,” In: Fleet, D., Pajdla, T., Schiele, B., Tuytelaars, T. (eds) *Computer Vision – ECCV 2014. ECCV, 2014. Lecture Notes in Computer Science*, vol. 8693. Springer, Cham. https://doi.org/10.1007/978-3-319-10602-1_48, [Online], Available: https://cocodataset.org/#home [Visited on 26. August 2022].

[11] M. Tan and Q.V. Le, “EfficientNet: Rethinking Model Scaling for Convolutional Neural Networks,” in *ArXiv*, abs/1905.11946, 2019.

[12] zylo117, “Yet-another-EfficientDet-Pytorch,” [Online], Available: https://github.com/zylo117/Yet-Another-EfficientDet-Pytorch [Visited on 26. August 2022].

Testbed for Functional Safety-Relevant Wireless Communication Based on IO-Link Wireless and 5G

Thomas Robert Doebbert, Henry Beuster, Gerd Scholl
Electrical Measurement Engineering
Helmut-Schmidt-University
Hamburg, Germany
firstname.lastname@hsu-hh.de

Florian Fischer, Dominik Merli
HSA_innos
University of Applied Sciences Augsburg
Augsburg, Germany
firstname.lastname@hs-augsburg.de

***Abstract*—In the field of industrial production automation, wireless networks support highly flexible manufacturing processes and enable technologies to set-up new production chains and future software businesses. The IO-Link Wireless (IOLW) protocol is an already established energy-efficient and cost-effective communication standard for smart sensor devices on the industrial shop floor, whereas the mobile communication standard 5G will be mainly applied for medium and long-range wireless communication applications promising low latency times and high reliability. Therefore, 5G with the coming enhancement of deterministic ultra-Reliable Low-Latency Communication (uRLLC) is combined with the robustness and low-latency performance characteristics of IOLW. Features of both technologies are highly beneficial to realize even highly demanding safety-related applications. The presented testbed shall qualify wireless functional safety communication with respect to its Residual Error Probability (REP) and quantify the Probability of Failure per Hour (PFH).**

***Index Terms*—5G, IO-Link Wireless, Functional Safety, Industrial Wireless Networks, Wireless Sensor Networks**

I. Introduction

In order to develop a suitable testbed to evaluate wireless applications in the field of functional safety, the wireless technologies employed with its specific advantages are vital to realize an all-wireless, software-defined, and safety-focused sensor-to-cloud automation system, which improves the flexibility of manufacturing processes and enhances the degree of interconnections of Cyber-Physical Systems (CPSs).

Key factors such as cycle time, bandwidth, availability, reliability, deterministic communication and security of wireless channels are important regarding its applicability. Therefore, testbeds are needed to find indicators of the key performance factors. Furthermore, it is essential to develop prediction methods for reliability and latency as well as protection goals for confidentiality, integrity, authenticity, and availability of the wireless system, which shall be operated in industrial environments in the domain of functional safety.

Next to security enhancements on its own, also the combination of safety and security in the communication of industrial automation is a broad field for research (e.g. [1], [2]). In the field IO-Link Wireless (IOLW), the combination of safety and security was investigated within a recent publication [3]. Other communication technologies may be investigated within future work.

In the following Section II, key technologies of functional safety-relevant wireless communication are described. In Section III, the safety requirements with its relevant parameter and necessary calculations are evaluated and in Section IV a possibility to validate and verify the testbed architecture solution approach is demonstrated. A conclusion and an outlook are given in Section V.

II. Key Technologies

The intended testbed with wireless safety-relevant communication, the specific technologies with features employing a testbed for safety-relevant wireless communication are presented in the following.

A. IO-Link Wireless

IOLW is the extension of the proven IO-Link standard [4] being known as Single-Drop Digital Communication Interface (SDCI) or IEC 61131-9 [5]. Sensor/actuator field-bus communication within the factory automation structure is the main usage of IOLW [4]–[7]. There are general surveys of IOLW as an open-vendor communication solution for factory automation on the shop floor in [7]–[9] with a focus on roaming in [10], antenna planning in [11], coexistence in [12], [13], security enhancement in [3], [14], [15], and functional safety [16], and on IOLW testing in [6], [17], [18]. Additionally, a short introduction to IOLW is given here.

IOLW supports bidirectional wireless communication for (cyclic) process data and (acyclic) on-request data between a Wireless Master (W-Master) and Wireless Devices (W-Devices) [19], [5] and, therefore, IOLW is directly intended by design for fast and reliable communication on the shop-floor with dedicated technical key system properties [7], [19]. IOLW operates in the 2.4 GHz ISM-band and its base station (i.e., W-Master) supports a star-topology. Without performance reduction within a single manufacturing cell with a distance of up to 20 m from the W-Master in total up to 120 sensor or actuator nodes can operate reliably. IOLW uses frequency hopping to mitigate fading effects due to multi-path propagation and to improve the coexistence behavior with other wireless systems [12], achieving a latency below 5 ms in typical industrial environments with a remaining failure

https://doi.org/10.24405/14544

probability of 10^{-9} [19]. Therefore, the average receive power must be sufficiently high and the system must not be interfered.

B. 5G Campus Network / Industrial 5G Campus Network

In the past, safety function response times in the order of 10 ms for safety applications up to Safety Integrity Level (SIL) 3 (e.g., [20]) are critical, because response times in this range were typically not guaranteed by legacy cellular technologies such as 4G. The 5G technology shall provide better performance factors (e.g., [21]) standardized in the 3GPP process [22].

The main application domains as universal communication solution for 5G networks are: enhanced Mobile Broadband (eMBB) with high data rates and transmission capacities for data and streaming applications, massive Machine Type Communication (mMTC) with a low power requirement, low complexity, low data rates and a high number and density of communication devices, and ultra-Reliable Low-Latency Communication (uRLLC) for communication with high reliability and very low latency [23]. In safety-relevant communication, uRLLC is the preferred configuration being stated in Rel-16 as services regarding high levels of reliability. Rel-16 also includes the integration of Time Sensitive Communication (TSC), and enhancements for private network deployments being fully isolated. Private campus networks are available with Rel-15 as the first full set of 5G standards and of particular interest for industrial applications [24]–[26]. Further support for private networks through neutral host models is introduced in Rel-17, allowing access to standalone private networks with third-party credentials, including public network operators. Key factors are here controlability and data sovereignty [27] being operated e.g., with a dedicated radio access network of 3.7 GHz band width and core network functions running in premises or in the cloud respectively at the service provider.

C. Open Platform Communications Unified Architecture

Open Platform Communications Unified Architecture (OPC UA), which is published as IEC 62541 [28], combines open-source and platform-independent industrial data-exchange with state-of-the-art IT security features for authentication, authorization and encryption. OPC UA defines basic transport protocols for different demands and may be mapped to other Ethernet-based protocols like AMQP and MQTT [29]. Besides the transport of live, real-time, historical or aggregated data, alerts, events and method-calls, OPC UA provides unified information models for the multi-provider-compatible semantic description of machines, plants and entire companies. It is designed as service-oriented architecture and supports client-server as well as publish-subscribe (PubSub) communication [29]. The core specification introduces in part 15 [30] an IEC 61784-3 compatible Safety Communication Layer (SCL) to ensure deterministic data exchange between safety-related devices. Therefore, the underlaying OPC UA channel according to the black channel-principle is used. For consistent integration into existing plants and applications several companion specification are released to unify the deployment of other communication protocols like IO-Link [31] and Profinet or to standardize the information model for use-cases and markets for example Robotics and MachineVision [29]. With regard to Industry 4.0 related topics such as cloud or edge computing and Industrial Internet of Things, the harmonized information model provides easy scalability, broad availability and high interoperability. To integrate the communication model of OPC UA down to the shop floor, the OPC Foundation is extending the standards towards controller-to-controller and controller-to-device communication under the name of OPC UA Field eXchange (OPC UA FX), which also includes Time Sensitive Networking (TSN).

D. Time Sensitive Networking

A key-factor for safety-related communication is the reliable and deterministic data transmission in converged Ethernet-based networks. TSN enables the transmission of real-time traffic besides best-effort traffic on the same Ethernet connection [32]. Next to time synchronization, bounded low latency in form of multiple schedulers, reliability and resource management are the basic parts of the TSN standards [33]. The specified features and key performance indicators enable convergent networks down to the field level with bump-less reconfiguration and scalable bandwidth. Due to the Ethernet-based specification, TSN may be integrated into other communication technologies such as OPC UA and 5G [24] for wireless applications.

This allows to converge all necessary communication streams to a single connected wire for each device. Multiple benefits for the domain of industrial processing are arising by this, but the development for domain specific standards e.g., IEC/IEEE 60802 for industrial automation is not completed yet.

However, the trend of converged network brings also new challenges, for instance the attack surface and number of potential threats towards the real-time communication domain increases. Therefore, by using the technology of TSN and its beneficial features, also security aspects and an effective protection strategy must be considered. Within the TSN specification 802.1Qci is the only standard, which addresses cyber security in from of per-stream filtering and policing. This filtering is based on layer 2 (according to the ISO/OSI model), since common firewalls work on layer 3/4 or upwards and would impact the real-time capability in a non-acceptable manner. The selection and effective integration of mitigation strategies and tools is a challenging task for the TSN domain and makes more in-depth research work necessary.

III. Measures for Safety Requirements

According to the IEC 61508 series of international standards on functional safety [34], any electrical, electronic or programmable electronic system performing safety-related functions must be developed under functional safety management to reduce the residual risks to people, equipment or the environment to an acceptable level. The required risk reduction is measured by the SIL scaled with four steps having necessary measures and values for key factors assigned. The SIL is evaluated in the risk analyses as the first step of the validation and verification (V&V) process, which describes the entire safety life cycle. Further aspects of the so-called V-model [5] are, for example, the definition of the Safety Requirement Specification (SRS), the system, hardware and software design, test concepts for each step, verification through testing and finally the validation of the safety system of the SRS. The safety-related system could be divided into subsystems, whereas each must meet the aspired SIL. This enables the deployment and combination of (pre-)certified commercial hardware and software components e.g., in distributed safety functions or even networks.

Certified fail-safe field-buses could be used to communicate between the subsystems. The corresponding IEC 61784-3 standard [35] contains guidelines that should be followed for the exchange of safety-related data in a distributed network. Based on the black channel principle as defined in [34], no safety validation of the communication channel used is necessary when the explained techniques are applied to the SCL and the developed Functional Safety Communication Profile (FSCP). This is advantageous for wireless connections over time-varying and frequency-selective radio channels, since there is no detailed knowledge about the channel needed. The standard recommends that the sum of failures contributed by communication should remain below one percent of the accepted Probability of Failure per Hour (PFH) of the corresponding target SIL. Exemplary, a SIL 3 application with less than 10^{-7} /h dangerous failures for the entire safety-function results in a Residual Error Rate (RER) for the entire SCL of 10^{-9} /h. To comply with [35], communication errors related to repetition, deletion, insertion, incorrect sequence, corruption, delay, masquerade and wrong addressing must be considered. There are deterministic measures to reduce the likelihood of these communication errors such as counter/inverted counter, timeout with receipt, time expectation, communication authenticity, receipt, data integrity and e.g., redundancy with cross-check. Furthermore, models are introduced to calculate values for error rates in the domain of authenticity, timeliness, masquerade and data integrity described below. The sum of these error rates results in the total RER (λ_{SC}) for the safety-channel.

A. Authenticity

To guarantee authenticity only correctly addressed massages from authenticated sources should be accepted. In the functional safety domain, this could be achieved by using connection-IDs as Authentication-Code (A-code) transmitted with every package. The A-code is transmitted explicit secured by integrity measures and the fact that the rate of misrouted messages shall not exceed the message rate of the system (v), the value for the RER for authenticity errors (RR_A) may be assumed with [35]:

$$RR_A = 0. \tag{1}$$

B. Timeliness

Communication errors, like delay or deletion, should be discovered to achieve the generic safety property of timeliness. Suitable methods are watchdogs, timestamps or counter values identifying the message with the Timeliness-Code (T-code). The contribution to λ_{SC} caused by timeliness errors is the RER for timeliness (RR_T) is

$$RR_T = 2^{-LT} \cdot w \cdot R_T \cdot RP_{FCSP\_T}, \tag{2}$$

with the bitlength of the T-code (LT), the number of accepted T-codes (w), the rate of not actual messages (R_T), which should be assumed in the worst case to v and additional Residual Error Probability (REP) of measures regarding timeliness (RP_{FSCP_T}).

C. Masquerade

If a non-safety message imitates a safety message undetected, all other safety requirements for authenticity, timeliness and integrity have to be fulfilled by coincidence or accident. Thus, the RER for masquerade (RR_M) will always be low and is defined as

$$RR_M = 2^{-LA} \cdot 2^{-LT} \cdot w \cdot 2^{-r} \cdot RP_u \cdot 2^{-LR} \cdot R_M, \tag{3}$$

with the bitlength of the A-code (LA), the bitlength (r) of the signature of the Cyclic Redundancy Check (CRC), the REP for other specific data fields marking a correct safety message (RP_U), bitlength of the redundant message part in case of redundancy with cross-check (LR) and the rate of occurrence of masked messages (R_M), which is set to 10^{-3}/h for every device by default.

D. Data Integrity

Data integrity is the basic requirement for any safe decision; therefore, it is necessary to ensure that corruption is detected with a high and determined probability by the SCL. In general, auxiliary redundancy must be added to double check the integrity of the data. Most popular are error-detecting codes such as CRC, which are also proposed by the standard. For the estimation of the RER for data integrity (RR_I), the probability for an error in one bit must be assumed together with the likelihood, that this error could be detected by the selected safety measure.

1) Bit error probability: The black channel principle, as used according to [35], is based on the Binary Symmetric Channel (BSC) model. This model pretends, that the probability for a bit error is equal for the transmission of a digital one or digital zero at every position and could be assumed to be

$$0 \leq BEP \leq 0.5. \tag{4}$$

Since there would be no communication possible with a higher error probability, the standard specifies a Bit Error Probability (BEP) of 10^{-2} to be considered unless a prove for a lower BEP is given. Within this field of study, an ongoing discussion about the combination of safety and security measure is running in the community, which is caused by the fact that some cryptographic algorithms change the probability distribution so that the assumed BSC is not preserved [1].

2) Properness of CRC generator polynomials: The likelihood that a CRC calculation on an erroneous message has the same result as the calculation on the original message is a degree for the properness of the CRC generator polynomial. This probability should be calculated for every possible data length of the FSCP explicit. If the value never exceeds the so-called conservative limit of 2^{-r}, where r is the CRC-bit length, the generator polynomial is called proper and the REP follows the calculation results.

3) Residual error rates: The REP for data integrity (RP_I) is given by the REP of the proper CRC with the specified BEP. The equation

$$RR_I = RP_I \cdot v \cdot RP_{FSCP\_I}, \tag{5}$$

with the REP of additional safety measures for data integrity (RP_{FSCP_I}) is the last part to quantify the RER for the entire safety communication layer per hour (λ_{SCL}) as

$$\lambda_{SCL} = (RR_T + RR_A + RR_M + RR_I) \cdot m, \tag{6}$$

with the maximum number of logical connections allowed (m) for the safety function.

By applying the mentioned principles, a SRS for a IO-Link Safety (IOLS) related fail-safe IOLW derivative is proposed and the FSCP could be assessed using the demonstrator [16].

IV. Assessment of the Testbed Architecture Solution Approach

The objective of the testbed is the V&V of the system and protocol design with the according SRS, which is often also integrated within a safety life cycle V-model evaluation for safety-relevant measures to assess its functionality in a test environment. Further evaluation may also include safety performance and system availability [36].

A. Validation of the Safety Requirement Specification

With the help of a certified organization, a SRS is reviewed to survey that all risks are identified in the evaluation to meet the specification. The certified organization also reviews the SRS regarding completeness, contradictions, and correctness. In our case, the main focus is the concept and architecture of IO-Link Wireless Safety (IOLWS) rather than hardware or software implementation of the SRS. Nevertheless, the parameter of the measures used in software to reduce risks are also reviewed. Therefore, measures such as plausibility test for the calculated λ_{SCL} are implemented and evaluated.

B. Verification of System and Protocol Design

The verification of the testbed architecture solution approach may be realized by means of analyses, reviews, or by using a demonstrator setup, which can be based on separated lab setups. For safety functions, it is necessary to use a Functional Design Specification (FDS), which may be completed by separate function tests or complete module tests.

Module tests may include hardware setup tests in a control cabinet, analysis of address ranges between modules, limit value analysis, or e.g. compliance tests with programming guidelines. In our research, the overall system design and the initial software structure is emphasizes on as well as the IOLWS protocol design. The hardware design will not be part of the module tests.

Function tests focus on the program functionality, which involve process simulations, parameter checks, and e.g. limit value tests. Therefore, various tests and analysis such as IO tests, acceptance tests, function tests, response time tests, or signal path tests are possible [34].

Furthermore, Factory Acceptance Tests (FATs) for functional safety functions are possible using EN ISO 13849-2 and EN 62061. In our case, function, response time, and signal path tests are performed by using a demonstrator performing a specific application, which is described in the following.

C. Demonstrator for Functional Safety-relevant Wireless Communication

In [37], a modular Sensor-2-Cloud Automation Topology (mS2CAT) for safe and secure wireless communication employing a 5G-IOLW Gateway is described. Multiple cells are depicted for wireless communication enhancing flexible operations supporting CPSs.

The mS2CAT of Figure 1 illustrates a roaming IO-Link Safety Device (FS-Device) being connected to an IO-Link Wireless Safety Bridge (FS-W-Bridge) (in the following described as IO-Link Wireless Safety Device (FS-W-Device)). In [19], the flexibility and mobility that a predefined W-Device is able to connect to multiple predefined W-Master cells (called roaming) is described.

Depending on the location of the Automated Guided Vehicle (AGV) or person wearing a emergency stop, the FS-W-Device is locked into Cell 1, Cell 2 or Cell n. A FS-W-Device is only allowed to be connected to one IO-Link Wireless Safety Master (FS-W-Master) at a time. When switching from one cell to another cell, the FS-W-Device must first disconnect from one FS-W-Master before connecting to another FS-W-Master. Between the cells, a commissioning must take place to enter another safety cell depending on the application. It is not possible to enter another cell before being connected to the specific FS-W-Master. If a safety cell is entered by accident, the cell must be set to a safe state. Time slots may vary for entering a safety cell without interrupting the manufacturing process.

The FS-W-Master in each safety cell is connected to an OPC UA server aggregating the FS-Data using the standard master interface as Fail-Safe Gateway (FS-Gateway) according

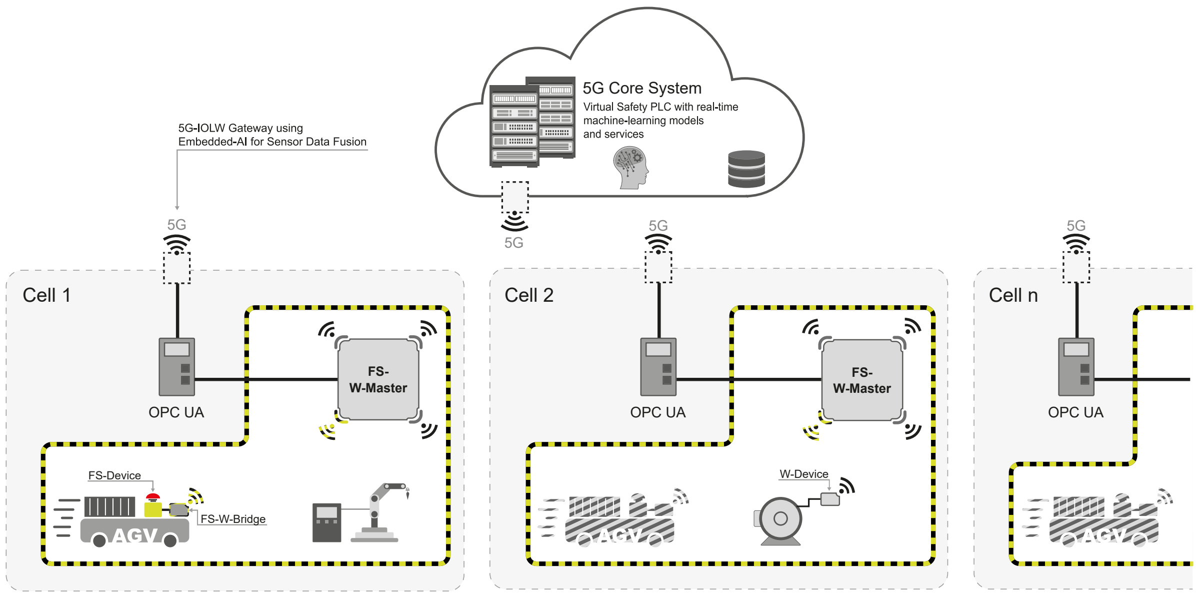


FIGURE 1. MODULAR SENSOR-2-CLOUD AUTOMATION TOPOLOGY (MS2CAT) FOR SAFE AND SECURE WIRELESS COMMUNICATION EMPLOYING A 5G-IOLW GATEWAY.

to [38]. The server in turn is accessed by a virtual safety Programmable Logic Controller (PLC) integrated into the 5G core system via 5G and a 5G modem module. To set up a continuous fail-safe communication from source to drain the mapping between IOLWS and OPC UA safety need to be designed compliant to [35], also OPC UA PubSub and TSC measures shall be taken into account to reduce latency and ensure deterministic response times. The described functions are combined as 5G-IOLW gateway and the OPC UA server as software service is integrated into either the FS-W-Master or the modem module. Both options shall be considered and compared as part of the project.

The testbed with the demonstrator shall be used to test modules and functions such as the IOLWS protocol, the response time between the 5G core system and the FS-Device using the black channel principle through two different wireless technologies as well as in-between the protocols, the signal path within safety-relevant states and the overall functionality. Tests will be part of the future evaluation of the testbed for functional safety-relevant wireless communication.

V. CONCLUSION AND OUTLOOK

In this contribution, a testbed for functional safety-relevant wireless communication based on IOLW and 5G is presented. Therefore, the well-known functional safety protocol IOLS is used in conjunction with a new introduced wireless communication protocol IOLWS. Furthermore, a gateway solution is enhanced to connect small-scale IOLWS in the short-range machine-area networks with medium-scale Industrial 5G in the medium-range factory area employing technologies such as TSN for deterministic communication and OPC UA for safe and secure distributed communication. For IOLWS the necessary SRS is described using IEC 61508 and IEC 61784-3. After assessment of the SRS, the testbed will be validated and verified using the described demonstrator for functional safety-relevant wireless communication.

In the next step, calculations for SRS will be evaluated and the testbed for the functional safety demonstrator will be realized.

ACKNOWLEDGMENT

This work is an extended continuation of the publications under [37], [39]. The authors would like to acknowledge Christoph Cammin and Ralf Heynicke from the Helmut-Schmidt-University as well as Kunbus GmbH for their continuous support.
This contribution is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge (project ”Digital Sensor-2-Cloud Campus Platform” (DS2CCP) with the project website [9]).

REFERENCES

[1] F. Schiller, D. Judd, P. Supavatanakul, T. Hardt, and F. Wieczorek, “Enhancement of safety communication model: Preserving the black channel concept,” *at - Automatisierungstechnik*, vol. 70, p. 38–52, 2022. [Online]. Available: https://doi.org/10.1515/auto-2021-0098

[2] F. Reichenbach, J. Endresen, M. M. R. Chowdhury, and J. Rossebø, “A Pragmatic Approach on Combined Safety and Security Risk Analysis,” in *2012 IEEE 23rd International Symposium on Software Reliability Engineering Workshops*, 2012, pp. 239–244.

[3] T. R. Doebbert, F. Fischer, D. Merli, and G. Scholl, “On the Security of IO-Link Wireless Communication in the Safety Domain,” in *2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2022, pp. 1–8.

[4] IO-Link Interface and System - Specification Version 1.1.3, June 2019, Order No: 10.002. [Online]. Available: https://io-link.com/share/Downloads/Package-2020/IOL-Interface-Spec_10002_V113_Jun19.pdf

[5] *IEC 61131-9:2022 Programmable controllers - Part 9: Single-drop digital communication interface for small sensors and actuators (SDCI)*, 2022. [Online]. Available: https://webstore.iec.ch/publication/68534

[6] C. Cammin, D. Krush, D. Krueger, and G. Scholl, "IO-Link Wireless Sensitivity Testing Methods in Reverberation Chambers, journal = Electronics," vol. 11, no. 17, 2022. [Online]. Available: https://www.mdpi.com/2079-9292/11/17/2775

[7] R. Heynicke, D. Krush, C. Cammin, G. Scholl, B. Kaercher, J. Ritter, P. Gaggero, and M. Rentschler, "IO-Link Wireless enhanced factory automation communication for Industry 4.0 applications," *Journal of Sensors and Sensor Systems*, vol. 7, p. 131–142, 2018. [Online]. Available: https://www.j-sens-sens-syst.net/7/131/2018/

[8] D. Wolberg, M. Rentschler, and P. Gaggero, "Simulative performance analysis of IO-Link Wireless," in *2018 14th IEEE International Workshop on Factory Communication Systems (WFCS)*. 2018 14th IEEE International Workshop on Factory Communication Systems (WFCS), 2018, pp. 1–10.

[9] Digital Sensor-2-Cloud Campus Platform. Project website: https://dtecbw.de/home/forschung/hsu/projekt-ds2ccp.

[10] M. Rentschler, "Roaming in wireless factory automation networks," in *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*. 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2017, pp. 1–4.

[11] C. Cammin, D. Krush, H. Wattar, R. Heynicke, and G. Scholl, "Base Station Antenna Placement of Wireless Sensor/Actuator Networks in Manufacturing Cells," in *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*. 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2019, pp. 1317–1320.

[12] C. Cammin, D. Krush, R. Heynicke, G. Scholl, C. Schulze, S. Thiede, and C. Herrmann, "Coexisting Wireless Sensor Networks in Cyber-Physical Production Systems," in *2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA)*. 2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA), 2016, pp. 1–4.

[13] D. Krush, C. Cammin, T. R. Doebbert, R. Heynicke, and G. Scholl, "Coexistence Management Methods and Tools for IO-Link Wireless," in *2021 17th IEEE International Conference on Factory Communication Systems (WFCS)*. 2021 17th IEEE International Conference on Factory Communication Systems (WFCS), 2021, pp. 151–158.

[14] T. Doebbert, C. Cammin, and G. Scholl, "Precision Measurement of the Application-dependent Current Consumption of a Wireless Transceiver Chip," in *SMSI 2021 - Measurement Science*. SMSI 2021 - Measurement Science, May 2021, pp. 281–282.

[15] T. Robert Doebbert, D. Krush, C. Cammin, J. Jockram, R. Heynicke, and G. Scholl, "IO-Link Wireless Device Cryptographic Performance and Energy Efficiency," in *2021 22nd IEEE International Conference on Industrial Technology (ICIT)*, vol. 1, 2021, pp. 1106–1112.

[16] T. R. Doebbert, C. Cammin, and G. Scholl, "Safety Architecture Proposal for Low-Latency Sensor/Actuator Networks using IO-Link Wireless," *IEEE Access*, vol. 10, pp. 3030–3044, 2022.

[17] C. Cammin, D. Krush, R. Heynicke, and G. Scholl, "Test method for narrowband F/TDMA-based wireless sensor/actuator networks including radio channel emulation in severe multipath environments," *Journal of Sensors and Sensor Systems*, vol. 7, p. 183–192, 2018. [Online]. Available: https://www.j-sens-sens-syst.net/7/183/2018/

[18] ——, "Employing correlation for wireless components and device characterization in reverberation chambers," *Journal of Sensors and Sensor Systems*, vol. 8, no. 1, pp. 185–194, 2019. [Online]. Available: https://jsss.copernicus.org/articles/8/185/2019/

[19] IO-Link Wireless System Extensions - Specification Version 1.1.3, June 2022, Order No: 10.112. [Online]. Available: https://io-link.com/share/Downloads/System-Extensions/IOLW-Spec_10112_V113_Jun22.pdf

[20] PROFIsafe Functional Safety. [Online]. Available: https://profinetuniversity.com/

[21] "Industrial 5G SLAs - industrial 5G network performance and the new turf war over the supply and management of 5G in Industry 4.0," pp. 27–28, April 2021, feature Report. [Online]. Available: https://f.hubspotusercontent40.net/hubfs/8928696/Editorial%20Programs/20210408%20Industrial%20Grade%205G%20SLA%20Editorial%20Report.pdf

[22] M. Baker and M. Poikselkä, "5G Releases 16 and 17 in 3GPP," Tech. Rep., 2020-04-20.

[23] A. Esswie and K. Pedersen, "Analysis of Outage Latency and Throughput Performance in Industrial Factory 5G TDD Deployments," December 2020. [Online]. Available: https://arxiv.org/abs/2012.05507

[24] A. Aijaz, "Private 5G: The Future of Industrial Wireless," *IEEE Industrial Electronics Magazine*, vol. 14, pp. 136–145, 2020.

[25] A. Alabbasi, T. Dudda, Z. Zou, and J. Kronander, "5G Toolbox for Realizing Industrial Automation," in *2019 IEEE 2nd 5G World Forum (5GWF)*. 2019 IEEE 2nd 5G World Forum (5GWF), 2019, pp. 512–515.

[26] S. Vitturi, C. Zunino, and T. Sauter, "Industrial Communication Systems and Their Future Challenges: Next-Generation Ethernet, IIoT, and 5G," *Proceedings of the IEEE*, vol. 107, pp. 944–961, 2019.

[27] G. A. for Connected Industries and A. (5G-ACIA), "5G Non-Public Networks for Industrial Scenarios," July 2019.

[28] *IEC 62541-1:2020 OPC Unified Architecture - Part 1*, 2020. [Online]. Available: https://webstore.iec.ch/publication/68039

[29] OPC UA Online Reference. [Online]. Available: https://reference.opcfoundation.org/

[30] "OPC Unified Architecture Part 15: Safety, Release 1.04," 2019-10-31. [Online]. Available: https://opcfoundation.org/developer-tools/specifications-unified-architecture/part-15-safety/

[31] (2018) OPC 30120 IO-Link Devices and IO-Link Masters. [Online]. Available: https://opcfoundation.org/developer-tools/documents/view/290

[32] J. Jasperneite, T. Sauter, and M. Wollschlaeger, "Why we need automation models: Handling complexity in industry 4.0 and the internet of things," *IEEE Industrial Electronics Magazine*, vol. 14, pp. 29–40, 2020. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9044672

[33] "IEC 60802:2020 Time-Sensitive Networking Profile for Industrial Automation, draft v1.2." [Online]. Available: https://www.ieee802.org/1/files/private/60802-d1-2.pdf

[34] *IEC 61508-1:2010 Functional safety of electrical/electronic/programmable electronic safety-related systems*, 2010. [Online]. Available: https://webstore.iec.ch/publication/5515

[35] *IEC 61784-3:2021 Industrial communication networks - Profiles - Part 3: Functional safety fieldbuses - General rules and profile definitions*, 2021. [Online]. Available: https://webstore.iec.ch/publication/62095

[36] P. Sanz, O. Seijo, M. C. Llorente, J. Montalban, P. Angueira, and I. Val, "On the feasibility of wireless communications for safety applications in industry," *IEEE Transactions on Industrial Informatics*, pp. 1–1, 2022.

[37] T. R. Doebbert, C. Cammin, G. Scholl, and B. Kärcher, "Study of a Safe and Secure Ecosystem based on IO-Link Wireless and a 5G Campus Network," in *2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*. 2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2021, pp. 1–4.

[38] IO-Link Safety System Extensions with SMI - Specification V1.1.3, March 2022, Order No: 10.092. [Online]. Available: https://io-link.com/share/Downloads/System-Extensions/IO-Link_Safety_System-Extensions_10092_V113_Mar22.pdf

[39] C. Cammin, T. Doebbert, B. Solzbacher, and G. Scholl, "Concept of a 5G Hybrid Wireless Campus Network as Testbed for Industrial Applications," in *Advances in System-Integrated Intelligence*. Cham: Springer International Publishing, 2023, pp. 458–469.

Beschreibungsmittel für die modellbasierte KI-Entwicklung in Automatisierungssystemen

Marvin Schieseck*, Philip Topalis*, René Heesch*, Julian Putzke*, Alexander Fay*
*Institut für Automatisierungstechnik
Helmut Schmidt Universität
Hamburg, Deutschland
Email: marvin.schieseck@hsu-hh.de

***Zusammenfassung*—KI-Anwendungen für Automatisierungssysteme sind komplexe und meist verteilte Systeme, an deren Entwicklung und Integration mehrere Fachdisziplinen beteiligt sind. Jede Fachdisziplin verwendet eigene, domänenspezifische Beschreibungsmittel zur Modellierung der Systemelemente. Ein interdisziplinäres Beschreibungsmittel, welches eine für alle Fachdisziplinen verständliche Modellierung der KI-Anwendung als Gesamtsystem ermöglicht, existiert bisher nicht. Häufig mangelt es deshalb an einem interdisziplinären Systemverständnis, was einen erhöhten Entwicklungs-, Integrations- und Wartungsaufwand zur Folge hat.**

In diesem Beitrag wird deshalb ein Beschreibungsmittel vorgestellt, das eine konsistente, grafische Modellierung von KI-Anwendungen für Automatisierungssysteme auf Systemebene erlaubt. Dadurch wird es möglich, einzelne Teilbereiche in domänenspezifische Teilsysteme zu untergliedern und so die bestehenden Aufwände zu reduzieren.

***Schlagworte*—Systemmodel, Beschreibungsmittel, KI-Anwendung**

I. Einleitung

Die Digitalisierung und Automatisierung von technischen Anlagen, Fertigungsprozessen und Produkten nimmt weiter zu und erhält neue Impulse durch moderne Informationstechnologien. Unternehmen sind dazu gezwungen, neue Technologien wie beispielsweise künstliche Intelligenz (KI) zu adaptieren, um auf dem internationalen Markt wettbewerbsfähig zu bleiben. [1]

Deshalb wird in den letzten Jahren vermehrt der Ansatz verfolgt, KI-Anwendungen in Automatisierungssysteme zu integrieren [2]. Es wurden bereits zahlreiche Anwendungsfälle identifiziert, in denen durch die Integration von KI die Effizienz der bisherigen Lösungen gesteigert oder überhaupt erst ermöglicht wurde [3]. Beispiele dafür finden sich im Bereich der Instandhaltung, der Qualitätskontrolle, der Bedarfsplanung oder der Anlagenplanung [4].

Trotz dieser vielversprechenden Anwendungsfälle wird KI in der Industrie insgesamt vergleichsweise noch wenig eingesetzt [1]. KI-Anwendungen werden häufig im Rahmen von Forschungsprojekten erarbeitet und können bisher oft nur in geringem Umfang wirtschaftlich in der Praxis integriert werden [4]. Dies ist zum Teil darin begründet, dass die Software-Entwicklung von KI-Systemen im Vergleich zur traditionellen Software-Entwicklung mit zusätzlichen Herausforderungen konfrontiert ist, welche eine wirtschaftliche Weiterentwicklung und Integration von experimentellen KI-Lösungen häufig verhindern. [5], [6]

In [5] wird darauf hingewiesen, dass die meisten dieser Herausforderungen auf der Systemebene und nicht auf der Codeebene gelöst werden müssen. Die Autoren zeigen auf, dass eine Möglichkeit für die abstrakte Systemmodellierung von KI-Systemen fehlt. In [7], [8] und [9] wird beschrieben, dass für produzierende Unternehmen kein interdisziplinärer Kommunikationsrahmen existiert, welcher ein einheitliches Verständnis von KI-Systemen ermöglicht und die grundsätzlichen Funktionen und Komponenten definiert. Der Handlungsbedarf für die Forschung wird in [10] zusammengefasst. Demnach mangelt es an interdisziplinären und leicht verständlichen Modellen für die Entwicklung von KI-Anwendungen, welche die Zusammenhänge zwischen den einzelnen Anlagenkomponenten, Softwarekomponenten und Prozessen gemeinsam modellieren und die Zusammenarbeit unterschiedlicher Fachdisziplinen fördern können.

Eine Möglichkeit, um diesen Handlungsbedarf zu adressieren, bietet eine grafische Darstellung des Systems. Dadurch kann der Kern eines Problems formal und verständlich für unterschiedliche Beteiligte modelliert und dargestellt werden [11], [12]. Im Bereich der Automatisierungstechnik und der Informatik werden grafische Darstellungen von Systemen deshalb häufig eingesetzt [13]. Ein Beschreibungsmittel ermöglicht die Definition der Symbole, der Regeln und der Semantik dieser Darstellung und dadurch eine für alle Fachdisziplinen verständliche Modellierung. Ein geeignetes Beschreibungsmittel für die Modellierung von KI-Anwendungen für Automatisierungssysteme existiert bisher nicht. Zur Schließung dieser Lücke wird in diesem Beitrag ein neues Beschreibungsmittel vorgestellt.

In Abschnitt II werden die Anforderungen aus dem Handlungsbedarf und den Herausforderungen abgeleitet. Außerdem wird ein Überblick über verwandte Arbeiten gegeben und offene Punkte der aktuellen Ansätze werden aufgezeigt. Anschließend wird in Abschnitt III das entwickelte Beschreibungsmittel vorgestellt. In Abschnitt IV werden zur Validierung KI-Anwendungen für zwei unterschiedliche industrielle Anwendungsfälle modelliert. Die Ergebnisse werden in Abschnitt V diskutiert und in Abschnitt VI zusammengefasst. Abschließend werden in Abschnitt VII zukünftige Forschungsthemen aufgezeigt.

https://doi.org/10.24405/14545

II. Anforderungen und verwandte Arbeiten

Die Software-Entwicklung von KI-Anwendungen ist im Vergleich zur traditionellen Software-Entwicklung mit zusätzlichen Herausforderungen konfrontiert. Diese sind unter anderem unklare Systemgrenzen, Rückkopplungsschleifen, nicht deklarierte Datenabhängigkeiten, Konfigurationsprobleme, Veränderungen in der Außenwelt sowie Anti-Patterns auf Systemebene, um nur einige zu nennen. Der geschriebene Code für die datenbasierten KI-Modelle besteht zumeist nur aus wenigen Zeilen Programmcode und ist im Verhältnis zur gesamten Software nur ein kleiner Teil. Der Großteil des KI-Systems besteht aus Konfiguration, Automatisierung, Testing, Ressourcenmanagement, Prozess- und Metadatenmanagement, Einsatzinfrastruktur sowie Datenerfassung, -speicherung, -übermittlung und -überprüfung. Ein weiteres Problem bei KI-Systemen besteht darin, dass alle Änderungen, die dazu führen, dass sich die zukünftigen Daten von den historischen Daten unterscheiden, negative Auswirkungen auf das gesamte KI-System haben. Das bedeutet, dass die Anpassung von Hardwarekomponenten wie beispielsweise einer Datenquelle, auch wenn dadurch die Datenqualität insgesamt verbessert wird, trotzdem negative Auswirkungen auf die gesamte KI-Anwendung haben kann. [5]

Erschwerend kommt hinzu, dass die meisten KI-Systeme für technische Anlagen dezentrale und verteilte Systeme darstellen, bei denen verschiedene Soft- und Hardwarekomponenten über das technische System verteilt sind [14].

A. Anforderungen an das Beschreibungsmittel

Aus dem Handlungsbedarf und den aufgezählten Herausforderungen für KI-Anwendungen werden nachfolgend die Anforderungen an das Beschreibungsmittel abgeleitet:

A1: Interdisziplinär leicht verständlich: Es muss branchenneutral und für alle beteiligten Fachdisziplinen leicht verständlich sein, um den Aufwand und die Hürde für die Anwendung gering zu halten und um eine einheitliche Kommunikationsgrundlage zu schaffen [10].

A2: Reduzierung der Symbolik: Es muss alle für die Entwicklung und den Betrieb notwendigen Informationen und Komponenten der KI-Anwendung, der Anlage und des Prozesses eindeutig und strukturiert darstellen können [10]. Es ist eine formale Reduktion auf eine definierte Menge von Symbolen für die Darstellung von Systemkomponenten erforderlich, ebenso wie Regeln für deren zulässige Verbindung [15]. Es muss eine symbolisch und semantisch verständliche Darstellung ermöglichen und dabei die Komponenten, Funktionen, Relationen berücksichtigen [11].

A3: Darstellen wechselseitiger Abhängigkeiten: Es muss physikalische und informationelle Abhängigkeiten zwischen Anlagenkomponenten, KI-Komponenten und dem Prozess erfassen und darstellen können, um die aufgezeigten Probleme für KI-Anwendungen auf Systemebene zu verhindern [10].

A4: Darstellung von unterschiedlichen KI-Softwarearchitekturen: Es muss die konzeptionelle Darstellung und Modellierung von unterschiedlichen KI-Softwarearchitekturen ermöglichen, um verschiedene, verteilte KI-Systeme als Lösung berücksichtigen zu können [5].

A5: Integration in KI-Vorgehensmodelle: Es muss entlang etablierter KI-Vorgehensmodelle verwendet und in diese integriert werden können, um den Mehraufwand so gering wie möglich zu halten [9]. Dies erfordert ein Zusammenspiel aus Vorgehensmodell und Beschreibungsmittel [13].

B. Vorgehensmodelle

Für die Entwicklung von komplexen technischen Systemen ist es üblich, Vorgehensmodelle einzusetzen. Diese definieren eine zeitlich logische Folge von Handlungen und unterstützen bei der Projektplanung und der zielorientierten Festlegung der Schritte eines Entwicklungsprozesses [13]. Als de facto-Standard für KI-Projekte hat sich hier der *Cross-Industry Standard Process for Data-Mining* (CRISP-DM) durchgesetzt [8], [16]. CRISP-DM ist ein domänenunabhängiges Vorgehensmodell, welches den Entwicklungsprozess in sechs Schritte unterteilt: *Business Understanding, Data Understanding, Data Preparation, Modelling, Evaluation und Deployment*. Es sind Iterationen und Rücksprünge zwischen einzelnen Schritten erlaubt [17]. CRISP-DM wird häufig als Basis für die Entwicklung von domänen- oder anwendungsfallspezifischen Vorgehensmodellen verwendet [16], [18]–[23].

C. Verwandte Modellierungssprachen und -konzepte

In [7] werden vier Komponenten beschrieben, aus denen ein KI-System aufgebaut ist und welche als Grundlage zur Modellierung verwendet werden: *Datenquelle, Datenverarbeitungskomponente, datengetriebenes Modell und KI-Service/Agent*. Für die grafische Darstellung werden Rechtecke und Kreise verwendet, welche entsprechend der Komponenten bezeichnet werden. Diese werden über Pfeile miteinander verbunden, um den Informations- und Datenfluss darzustellen. Die Datenquelle zeichnet die geforderten Daten auf und übersendet diese an andere Komponenten. Die Datenverarbeitungskomponente ist im engeren Sinne eine Funktion, welche die Eingabedaten in Ausgabedaten eines gewünschten Formats umwandelt. Das datengetriebene Modell wandelt ebenfalls Eingabedaten in Ausgabedaten, allerdings werden dafür ausschließlich datengetriebene Modelle eingesetzt, wie beispielsweise neuronale Netze, welche zuvor trainiert werden müssen. Der KI-Service/Agent verwendet für die Eingabedaten ausschließlich die Ausgabe eines datengetrieben Modells und wandelt diese in Ausgabedaten oder Aktionen innerhalb des technischen Gesamtsystems um.

In [24] wird ein Konzept zur Entwicklung von Industrie 4.0 Lösungen, zu denen auch KI-Anwendungen zählen, vorgestellt. Dieses Konzept wird als *NAMUR Open Architecture* (NOA) bezeichnet. Es basiert auf einer Ergänzung der klassischen Automatisierungspyramide und definiert zwei getrennte Bereiche: einerseits eine deterministische Kern-Prozessautomatisierung und andererseits Monitoring- und Optimierungs-Bereich. Die grafische Darstellung erfolgt über Rechtecke, welche entsprechend der gewünschten Komponenten bezeichnet werden. Jede der bezeichneten Komponenten wird in einen der beiden Bereiche eingruppiert und auf Basis der Automatisierungspyramide hierarchisch angeordnet. Die Modellierung der KI-Anwendung erfolgt dann, indem die Komponenten aus beiden Bereichen durch Datenschnittstellen mithilfe von Pfeilen miteinander verbunden werden.

Die Unified Modelling Language (UML) ist eine grafische Modellierungssprache, welche insbesondere im Bereich der Informatik zum Modellieren von Softwaresystemen verwendet wird. UML stellt 14 grafische Modellierungsarten (Diagramme) zur Verfügung, mit deren Hilfe Skizzen und Entwürfe eines Systems erstellt werden können. Für jedes Diagramm ist eine eigene Symbolik mit eigenen Regeln und eigener Semantik definiert. [25]

SysML ist eine auf UML basierende grafische Modellierungssprache, welche insbesondere im Bereich des Systems Engineering zur Modellierung verschiedener komplexer, technischer Systeme verwendet wird. SysML stellt, wie UML, diverse grafische Modellierungsarten (Diagramme) zur Verfügung, wobei die meisten auf UML basieren oder davon abgeleitet sind. [26]

In der VDI 3682 ist eine grafische Modellierungssprache definiert, welche zur Modellierung von technischen Prozessen im gesamten Lebenslauf technischer Systeme eingesetzt wird. Die Elemente dieser formalisierten Prozessbeschreibung sind Produkt (Kreis), Energie (Raute) und Prozessoperator (Rechteck), welche durch einen Flusspfeil (Volllinie mit Pfeil) miteinander verbunden werden. Durch den Prozessoperator werden Produkte und Energien entlang Flusspfeils umgewandelt. Der Prozessoperator realisiert diese Umwandlung mithilfe eines weiteren Elements, der technischen Ressource (Rechteck mit abgerundeten Ecken). Technische Ressourcen und Prozessoperatoren werden einander über einen Nutzungspfeil (Strichlinie mit Pfeilen) zugewiesen. [27]

D. Bewertung der verwandten Arbeiten

Die etablierten Vorgehensmodelle unterstützen bei der Planung der zeitlichen Abfolge der einzelnen Schritte innerhalb des Projekts, aber kaum beim Entwurf oder der Modellierung der KI-Anwendung. Keines der Vorgehensmodelle definiert ausreichend, wie das System entlang der einzelnen Schritte modelliert und dokumentiert werden sollte. Es wird auch nicht auf ein geeignetes Beschreibungsmittel oder eine Modellierungssprache verwiesen. [16], [18]–[23]

Deshalb werden nachfolgend die bereits vorgestellten Ansätze mit den Anforderungen verglichen, um deren Eignung bezüglich der Modellierung zu bewerten.

Die Modellierung nach [7] besteht aus wenigen Symbolen und Regeln und wird deshalb als leicht verständlich bewertet (A1). Der Fokus liegt auf der Darstellung der KI-Anwendung. Eine Einschränkung, welche grundlegenden Komponenten und Funktionen berücksichtigt werden müssen, erfolgt nur für die KI-Anwendung (A2). Die Anlagenkomponenten oder der technische Prozess werden nicht berücksichtigt, mit Ausnahme des Sensors. Deshalb können die Abhängigkeiten zwischen den KI-Komponenten selbst modelliert werden, aber nicht zwischen dem Prozess oder den Anlagenkomponenten (A3). Die Darstellung von unterschiedlichen KI-Softwarearchitekturen ist nicht möglich, weil die Anlagenstruktur kaum berücksichtigt werden kann (A4). Die Autoren schlagen ein eigenes Vorgehensmodell vor, bestehend aus den Schritten: *Planen, Experimentieren, Implementieren* und *Optimieren*. Ein Vergleich dieser Schritte mit denen in CRISP-DM zeigt, dass der Ansatz bedingt integriert werden kann (A5).

Die Modellierung nach [24] mithilfe der NOA besteht aus wenigen Symbolen und Regeln und wird deshalb als leicht verständlich bewertet. Die Verständlichkeit wird dadurch gesteigert, dass die weit verbreitete Automatisierungspyramide als Basis verwendet wird (A1). Eine Einschränkung, welche grundlegenden Komponenten und Funktionen berücksichtigt werden müssen, erfolgt nur für einzelne Anlagenteile und KI-Komponenten (A2). In der NOA werden einzelne KI- und Anlagenkomponenten berücksichtigt, aber nicht der Prozess. Deshalb können die Abhängigkeiten zwischen KI-Komponenten und Anlagenkomponenten teilweise modelliert werden, aber nicht mit Bezug zum Prozess (A3). Auch die Darstellung von unterschiedlichen KI-Softwarearchitekturen ist nur eingeschränkt möglich, insbesondere durch Trennung in die zwei Bereiche. Dadurch wird vorwiegend eine Modellierung von Cloud-Architekturen unterstützt (A4). In [24] wird nicht beschrieben, wie das Konzept in etablierte Vorgehensmodelle integriert werden kann (A5).

Die grafische Modellierung mit UML oder SysML unter Verwendung und Kombination von verschiedenen Diagrammen ermöglicht prinzipiell die Modellierung von wechselseitigen Abhängigkeiten und von unterschiedlichen Softwarearchitekturen (A3)(A4). Beides sind allerdings umfangreiche Modellierungssprachen, welche zunächst von allen Beteiligten gelernt werden müssen, bevor sie verstanden und genutzt werden können. Jedes der Diagramme besitzt seine eigenen Symbole, Regeln und Semantik. Zusammenfassend werden diese Modellierungssprachen deshalb für die Entwicklung von KI-Anwendungen als interdisziplinär nicht leicht verständlich bewertet (A1). Die Symbolik der einzelnen Diagramme ist zwar definiert, allerdings ist diese nicht auf die wichtigen Komponenten für KI-Anwendungen reduziert (A2). Prinzipiell ist es möglich, verschiedene Diagramme in die einzelnen Schritte der etablierten Vorgehensmodelle zu integrieren (A5).

Die grafische Modellierung nach der VDI 3682 besteht aus wenigen Symbolen und Regeln und wird deshalb als leicht verständlich bewertet (A1). Die Symbolik ist reduziert auf grafische Elemente für Anlagenkomponenten und den Prozess, jedoch nicht für Software- oder KI-Komponenten (A2). Es werden wechselseitige Abhängigkeiten zwischen dem Prozess und den Anlagenkomponenten erfasst, jedoch nicht zu den KI-Komponenten. Durch eine Zuordnung von Software-Komponenten zu technischen Ressourcen mithilfe eines Informationsmodells kann nachvollziehbar dokumentiert werden, welcher Anteil von welcher Software auf welcher technischen Ressource läuft und welchem Prozessschritt dies zugeordnet ist [28]. Softwarekomponenten sowie Daten- und Informationsflüsse können nur eingeschränkt erfasst und nicht grafisch dargestellt werden (A3). Deshalb ist auch die Darstellung von unterschiedlichen KI-Softwarearchitekturen nicht möglich (A4). Die VDI 3682 kann in den Schritt Busines Understanding integriert werden, ist aber für die folgenden Schritte nicht geeignet (A5). In TABELLE I wird die Bewertung der bestehenden Ansätze tabellarisch zusammengefasst.

III. ERARBEITUNG DES BESCHREIBUNGSMITTELS

Nach [11] können allgemeine Systeme mithilfe der folgenden vier Elemente beschrieben werden: *Systemkomponenten, Systemfunktionen, Systemrelationen* und *Systemstrukturen*. Für das Beschreibungsmittel werden diese Systemelemente definiert, mit dem Ziel, die aufgelisteten Anforderungen zu erfüllen.

A. Systemkomponenten

Die Systemkomponenten definieren die Bausteine, aus denen das System aufgebaut ist [11]. Entsprechend der Anforderungen werden für das Beschreibungsmittel zwei Arten von Systemkomponenten definiert: Produkte und technische Ressourcen. Produkte sind die Materialien, die während eines Prozesses innerhalb der Automatisierungsanlage transformiert werden. Technische Ressourcen sind die Anlagenkomponenten, aus denen die reale Anlage aufgebaut ist und welche die Systemfunktionen ausführen. Für das Beschreibungsmittel werden sechs zulässige Kategorien von technischen Ressourcen definiert:

- Sensoren: Geräte, die Messewerte aus einem Prozess in der Anlage erfassen und digitalisieren.
- Aktoren: Geräte, die steuernd in einen Prozess in der Anlage eingreifen.
- Steuerungen: Geräte, welche für die gerichtete Beeinflussung des Verhaltens des technischen Systems verantwortlich sind. Die Verarbeitung von Signalen erfolgt in kurzen, bei Bedarf deterministischen, Zyklen.
- Edge-Geräte: Mikrocontroller oder Computer, die lokal in der Anlage und damit nahe am Prozess befindlich sind.
- Lokale Computersysteme: Unternehmensinterne Rechenzentren, die über das Unternehmensnetzwerk und ohne Internetverbindung erreichbar sind.
- Cloudsysteme: Unternehmensexterne Rechenzentren, die nur mit einer Internetverbindung erreichbar sind.

B. Systemfunktionen

Systemfunktionen wandeln eine Eingabemenge in eine Ausgabemenge um und ermöglichen es dadurch, die Ziele des Systems zu erreichen [11]. Funktionen können von technischen Ressourcen ausgeführt werden. Im Rahmen des Beschreibungsmittels werden sieben Kategorien von Systemfunktionen definiert:

- Automatisieren: Sensorwerte einlesen, verarbeiten und anschließend Aktoren ansteuern, um einen Prozess in der Anlage zielgerichtet zu beeinflussen. Diese Funktion beschreibt, dass ein Prozess automatisiert durch Ausführen von Steuerungscode in der Anlage abläuft.
- Transformieren: Reale Eingangsprodukte in Ausgangsprodukte umwandeln, zum Beispiel ein Halbzeug in ein Werkstück durch einen Zerspanungsprozess.
- Aufnehmen: Physikalische oder chemische Eigenschaften (Druck, Temperatur) erfassen und digitalisieren. Ebenfalls zur Aufnahmefunktion zählt das Erfassen von nicht physikalisch oder chemischen Daten, also beispielsweise Zeiten (Datum, Uhrzeit) oder wirtschaftlichen Daten (Kurse, Preise, Bestände).
- Speichern: Daten nach einer definierten Systematik, für eine definierte Zeit an einem definierten Speicherort ablegen.
- Verarbeiten: Eingabedaten oder -messwerte durch einen definierten Algorithmus in Ausgabedaten umwandeln. Beispielsweise zur Datenvorverarbeitung oder -nachverarbeitung. Es darf kein datengetriebener Algorithmus verwendet werden.
- Trainieren: Anpassen der Parameter eines datengetriebenen Algorithmus auf einen Anwendungsfall mithilfe von historischen Daten.
- Inferieren: Eingabedaten oder -messwerte durch einen datengetriebenen Algorithmus in Ausgabedaten umwandeln. Der datengetriebene Algorithmus muss bereits konfiguriert und parametriert sein, beispielsweise durch das Training.

C. Systemrelationen

Durch Systemrelationen werden die Verbindungen und Beziehungen zwischen Systemelementen beschrieben [11]. Dadurch können Abhängigkeiten ermittelt und dargestellt werden. Im Rahmen des Beschreibungsmittels werden drei Kategorien von Systemrelationen definiert:

- Kommunikation: Eine informationstechnische Verbindung zwischen zwei Systemkomponenten, welche den Informationsaustausch zwischen beiden beschreibt, beispielsweise zwischen Steuerung und Sensor.
- Zuordnungen: Eine strukturelle Verbindung zwischen Systemfunktionen und Systemkomponenten. Dadurch werden den Systemkomponenten die Systemfunktionen zugewiesen. Beispielsweise der Systemkomponente Sensor die Funktion Aufnehmen.
- Material- und Energiefluss: Eine energie- oder materialtechnische Verbindung zwischen Produkten und einer Transformationsfunktion.

D. Systemstruktur

Durch die Systemstruktur wird das Ordnungsprinzip, nachdem die einzelnen Komponenten des Systems strukturiert werden, definiert [11]. In der Automatisierungstechnik ist die Automatisierungspyramide eine akzeptierte, weit verbreitete und leicht verständliche Möglichkeit, die Anlagenstruktur zu ordnen und zu hierarchisieren [29], [30]. In Anlehnung daran wird für das Beschreibungsmittel eine vierstufige Systemstruktur definiert:

TABELLE I
BEWERTUNG VON MODELLIERUNGSSPRACHEN UND -KONZEPTEN FÜR KI-ANWENDUNGEN FÜR AUTOMATISIERUNGSSYSTEME

	A1: Interdisziplinär leicht verständlich	A2: Reduzierung der Symbolik	A3: Darstellen wechselseitiger Abhängigkeiten	A4: Darstellung unterschiedlicher KI-Softwarearchitekturen	A5: Integration in KI-Vorgehensmodelle
Kaymacki [7]	●	◐	◐	○	◐
NOA [24]	●	◐	◐	◐	○
UML/SysML	○	○	●	●	●
VDI 3682 [27]	●	◐	◐	○	◐

● Anforderung erfüllt ◐ Anforderung teilweise erfüllt ○ Anforderung nicht erfüllt

- Ebene 1 physikalische Prozesse: Hier werden Transformationsprozesse der Produkte innerhalb der Automatisierungsanlage beschrieben.
- Ebene 2 Feldgeräte: Hier werden die Sensoren und Aktoren beschrieben.
- Ebene 3 Steuerungs- und Kontrollsysteme: Hier werden die Steuerungen und Edge-Geräte beschrieben.
- Ebene 4 Computer- und Cloudsysteme: Hier werden lokale und externe Computer- und Cloudsysteme beschrieben.

E. Symbole des Beschreibungsmittels

Eine standardisierte Symbolik der definierten Systemelemente ermöglicht es, den Entwicklungsprozess zu vereinfachen. Außerdem können die Ergebnisse der Entwicklung präziser kommuniziert und dokumentiert werden [15]. Deshalb wird eine einheitliche Symbolik für die Systemfunktionen, Systemkomponenten und Systemrelationen definiert.

Für die Systemfunktionen werden Rechtecke verwendet. Für die technischen Ressourcen werden Rechtecke mit abgerundeten Ecken und für die Produkte werden Kreise verwendet. Die Kommunikationsbeziehungen werden durch Volllinien dargestellt, wobei die Kommunikationsrichtung durch Pfeile definiert wird. Die Zuweisung von Systemkomponenten und Funktionen erfolgt mithilfe einer Strichlinie. Der Materialfluss wird ebenfalls durch eine Strichlinie dargestellt, wobei der Pfeil die Flussrichtung definiert. Ein Überblick der Symbole ist in ABBILDUNG 1 abgebildet.

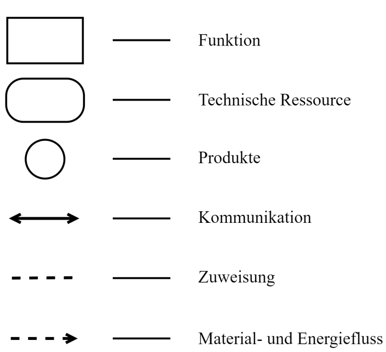


ABBILDUNG 1. ÜBERBLICK DER GRAFISCHEN SYMBOLE DES BESCHREIBUNGSMITTELS ZUR MODELLIERUNG.

F. Methodik zur grafischen Modellierung

Damit das Beschreibungsmittel in die etablierten Vorgehensmodelle integriert werden kann, muss es einzelne Schritte von CRISP-DM unterstützen. Im ersten Schritt von CRISP-DM werden Business- und Projektziele definiert, beispielsweise, dass die Wartungskosten einer Teilanlage reduziert werden sollen. Gleichzeitig werden auch technische Zusammenhänge betrachtet und mit dem Business-Ziel verglichen, um technisch relevante Parameter zu definieren. Also zum Beispiel, dass ein Großteil der Wartungskosten auf die Reparatur einer bestimmten Anlagenkomponente zurückgeführt werden kann. Während dieses Schritts kann das Beschreibungsmittel zur Modellierung des Ist-Stands der Anlage und des Prozesses eingesetzt werden. Dies ermöglicht es, den Problemraum zu formalisieren, zu dokumentieren und zwischen allen Beteiligten zu kommunizieren. Anschließend kann gemeinsam von allen Beteiligten ein Lösungsraum erarbeitet werden. In den einzelnen Schritten des CRISP-DM kann das grafische Modell sukzessive erweitert und angepasst werden, um die KI-Anwendung zu entwickeln. Für die grafische Modellierung wird folgende Methodik empfohlen:

Es sollte zunächst der Ist-Stand des technischen Systems entlang der Ebenen von unten nach oben modelliert werden. Also beginnend bei der Prozessebene, über die Feldgerät und Steuerungsebene bis in die Computer- und Cloudsystemebene, jeweils mit den Systemkomponenten, -relationen und -funktionen, welche die technisch relevanten Parameter beeinflussen. Anschließend werden mögliche Lösungskonzepte für die KI-Anwendung auf Systemebene erarbeitet, indem zusätzliche Systemkomponenten, -funktionen und -beziehungen hinzugefügt oder bestehende geändert werden. Je nach Kombination und Verteilung von KI-Funktionen, Anlagenkomponenten und Kommunikationsbeziehungen können dann unterschiedliche KI-Softwarearchitekturen konzeptioniert und miteinander verglichen werden. Nachfolgend wird die vorgeschlagene Methodik zusammengefasst:

- Schritt 0: Businessziel, technisches Problem und relevante Parameter definieren.
- Schritt 1: Modellierung der Prozessschritte, der Produkte und des Materialflusses in der Prozessebene.
- Schritt 2: Modellierung der Feldgerätebene mit Zuweisungen von technischem Prozess, Produkt und Funktion.
- Schritt 3: Modellierung der Steuerungs- und Kontrollsystemebene mit Kommunikationsbeziehungen und Zuweisung von Funktionen.
- Schritt 4: Modellierung der Computer und Cloudsystemebene mit Kommunikationsbeziehungen und Zuweisung von Funktionen.

- Schritt 5: Modellierung von Lösungskonzepten durch Ergänzen von erforderlichen Systemfunktionen, -komponenten und -beziehungen.

IV. Validierung

Das Beschreibungsmittel wird zur Validierung in zwei Anwendungsfällen in einer Fertigungsanlage angewendet. Dafür werden zwei unterschiedliche KI-Anwendungen für zwei unterschiedliche technische Systeme modelliert.

A. Anwendungsfall 1: Predictive Maintenance

Im ersten Anwendungsfall sollen die Wartungskosten für einen Anlageteil reduziert werden. Dieser Anlagenteil führt einen Prozess aus, bei dem eine Glasscheibe mit Polyurethan umschäumt wird. Ziel ist, die Instandhaltungsstrategie des Antriebsriemens zu optimieren, indem ein geeigneter Wartungszeitpunkt vorausgesagt wird. Gegenwärtig wird der Riemen in festen Intervallen gewartet. Eine Befragung des Anlagenbetreibers hat ergeben, dass ein wartungsbedürftiger Antriebsriemen eine Schwingung bei der Positionierung eines Werkzeugs hervorruft. Aus den Messwerten, die während des Positionierens dieses Werkzeugs aufgezeichnet werden, soll deshalb auf den Riemenverschleiß geschlossen werden. Für die automatisierte Analyse der Positionsdaten und einen Rückschluss auf den Zustand des Riemens soll eine KI-Anwendung entwickelt und in die Anlage eingebettet werden.

Die Anlage besteht aus einem Trägergestell, einem festen unteren Gesenk und einem beweglichen oberen Gesenk. Das obere Gesenk wird von zwei Elektromotoren bewegt, wobei jeweils rechts und links am Trägergestell ein Elektromotor montiert ist. Die Kraftübertragung erfolgt auf jeder Seite über die besagten Antriebsriemen und die Position des Gesenks wird über Positionssensoren gemessen. Das Schäumwerkzeug selbst besteht aus einer oberen und einer unteren Werkzeugform, wobei an jedem Gesenk eine Form montiert ist.

Modellierung der Prozessebene: Zu Beginn des Fertigungsprozesses wird eine Scheibe in die untere Werkzeugform eingelegt. Anschließend wird das obere Gesenk heruntergefahren und die beiden Werkzeugformen werden aufeinander abgesetzt. Sobald beide Werkzeugformen geschlossen aufeinander liegen, wird das Polyurethan eingeschossen und die Scheibe umschäumt. Nach einer definierten Zeit werden die Werkzeugformen geöffnet und die Scheibe zur Nachverarbeitung entnommen. Die Prozessebene ist in Abbildung 2 in der Ebene 1 abgebildet.

Modellierung der Feldgerätebene: Die beiden Positionssensoren messen die Lage des oberen Gesenks während der Prozessschritte Schließen und Öffnen. Deshalb wird beiden Sensoren eine Aufnahmefunktion zugewiesen. In Abbildung 2 wird mit der Ebene 2 diese Feldebene modelliert.

Modellierung der Steuerungs- und Kontrollsystembene: Die Lagesensoren übermitteln die Positionsdaten an die Motorsteuerung. Der Motorsteuerung wird eine Automatisierungsfunktion zugewiesen, welche die direkte Steuerung und Positionierung der Motoren und damit die Positionierung des Gesenks übernimmt. Die Maschinensteuerung koordiniert den Fertigungsprozess, beispielsweise durch Vorgabe von Fertigungsparametern oder von Start- und Stop-Befehlen. Dazu kommuniziert sie unter anderem mit der Motorsteuerung. Der Maschinensteuerung wird deshalb ebenfalls eine Automatisierungsfunktion zugewiesen. Sie ist auch die Schnittstelle zum Anlagenbediener. Zusätzlich werden bei ihr die Zeitstempel aufgezeichnet, weshalb ihr eine Aufnahmefunktion zugewiesen wird. In Abbildung 2 wird mit der Ebene 3 der bisherigen Modellierung die Steuerungs- und Kontrollsystemebene hinzugefügt. Dadurch ist der Ist-Zustand des Systems modelliert.

Modellierung des Lösungskonzepts: Für den Betreiber ist es ausreichend, wenn das Ergebnis der Analyse der Riemenspannung bei Bedarf abgefragt werden kann. Es handelt sich nicht um eine Anwendung, die in Echtzeit bezogen auf den Prozess ausgeführt werden muss. Deshalb wird eine Cloud-Architektur für das Lösungskonzept gewählt. In der Cloud werden die Daten gespeichert und vorverarbeitet. Das Training des Modells und die Inferenz erfolgen auch in der Cloud. Das Ergebnis der Inferenz wird nachverarbeitet, sodass es von der Maschinensteuerung verwendet werden kann. Zusammengefasst werden der Cloud also Speicher-, Inferenz-, Trainings- und Verarbeitungsfunktionen zugewiesen. Über ein Edge-Gerät kommunizieren Maschinensteuerung und Cloud miteinander und tauschen Messdaten sowie Analyseergebnisse aus. Die Analyseergebnisse werden von der Maschinensteuerung auf einem Display für den Anlagenbediener dargestellt. Dafür wird der Maschinensteuerung eine Nachverarbeitungsfunktion zugewiesen. Das Lösungskonzept für die KI-Anwendung ist in Abbildung 2 dargestellt.

B. Anwendungsfall 2: Optische Qualitätssicherung

In diesem Anwendungsfall soll die Produktqualität der mit Polyurethan (PUR) umschäumten Glasscheiben erhöht und gleichzeitig dokumentiert werden. Das Umschäumen von Glasscheiben mit PUR erfordert den Auftrag eines Primers an den zu umschäumenden Flächen der Glasscheibe. Der Primer dient dabei als Haftvermittler für Glasoberflächen. Der Vorgang des Primerauftrags erfolgt in einer Fertigungszelle, welche einen Roboter, eine Auftragseinheit sowie eine Kamera umfasst. Die Auftragseinheit besteht aus einem Schwamm für den Auftrag des Primers auf die Scheibe, einer Dosiereinheit zu Befeuchtung des Schwamms sowie einer Dosiersteuerung zur Steuerung der Mengendosierung der Dosiereinheit.

Modellierung der Prozessebene: Zu Beginn des Prozesses nimmt der Roboter die mit einem RFID-Tag versehene Scheibe auf und führt diese an dem Schwamm der Auftragseinheit in einer Reihe von Fahraufträgen entlang. Hinter der Auftragseinheit ist eine Kamera stationiert, mit deren Hilfe der Primerauftrag über einen Bilderstrom aufgenommen und kontrolliert wird.

Modellierung der Feldgerätebene: Während die Glasscheibe durch den Roboter am Schwamm entlang bewegt wird, befeuchtet die Dosiereinheit den Schwamm mit dem Primer. Dies führt dazu, dass der Primer auf die Glasscheibe aufgetragen wird. Die Kamera nimmt Bilder des Primerauftrags

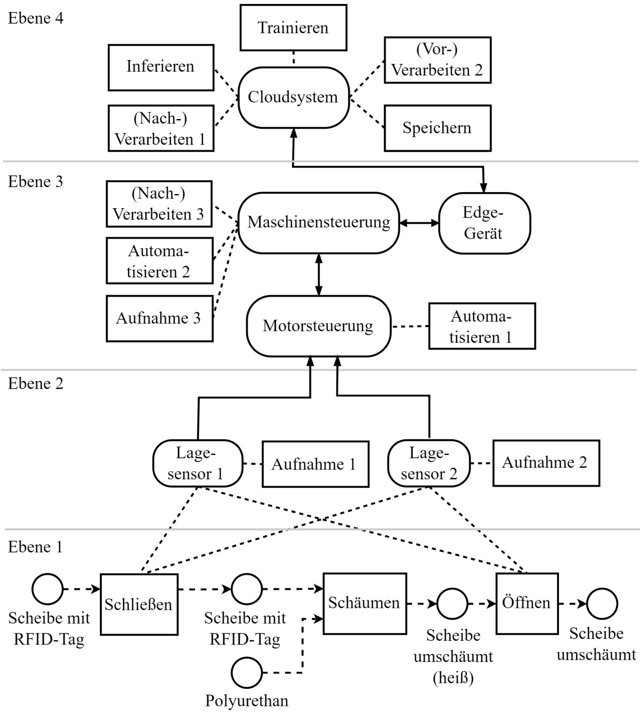


ABBILDUNG 2. MODELLIERUNG DES LÖSUNGSKONZEPTS FÜR DEN ERSTEN ANWENDUNGSFALL.

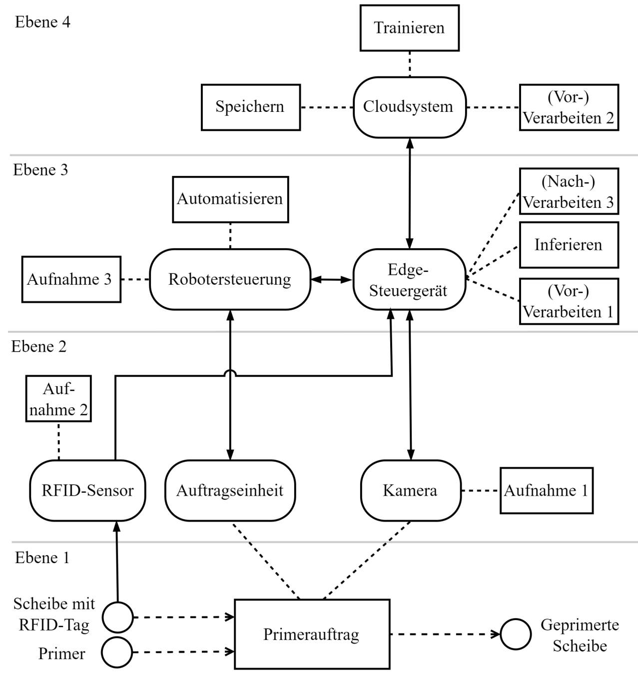


ABBILDUNG 3. MODELLIERUNG DES LÖSUNGSKONZEPTS FÜR DEN ZWEITEN ANWENDUNGSFALL.

auf, sodass dieser eine Aufnahmefunktion zugewiesen wird. Zur Nachverfolgbarkeit der Produktqualität nimmt der RFID-Reader die Identifikationsnummer der Glasscheibe auf. Dies ermöglicht die eindeutige Zuordnung der aufgenommenen Bilder zu der entsprechenden Glasscheibe. Somit wird auch dem RFID-Reader eine eigene Aufnahmefunktion zugewiesen.

Modellierung der Steuerungs- und Kontrollsystemebene: Der Robotersteuerung wird eine Automatisierungsfunktion zugeordnet, welche sowohl die direkte Steuerung des Roboters zur Ausführung der geplanten Trajektorien als auch die Steuerung der Dosiereinheit übernimmt.

Modellierung des Lösungskonzepts: Um die Haftung des PUR auf der Glasscheibe zu gewährleisten, muss die Primerauftragsfläche vollständig, das heißt ohne Fehlstellen, benetzt sein. Im Falle von zu wenig aufgetragenem Primer besteht die Gefahr, dass sich das PUR von der Glasscheibe löst. Dazu müssen die von der Kamera aufgenommenen Bilder ausgewertet werden. Diese Auswertung erfolgt über ein Edge-Steuergerät mithilfe einer KI-Anwendung. Dies erfordert ein rechenintensives Training des KI-Modells, welches nicht auf dem ressourcenbeschränkten Edge-Steuergerät ausgeführt werden kann. Aus diesem Grund werden die aufgenommenen Bilder über das Edge-Steuergerät in die Cloud übertragen und dort gespeichert. Innerhalb der Cloud werden die Bilddaten vorverarbeitet und das KI-Modell trainiert. Dementsprechend werden der Cloud eine Speicher-, Vorverarbeitungs- und Trainingsfunktion zugewiesen. Das Ziel ist die direkte Nacharbeitung bei der Erkennung von Fehlstellen, sodass es sich hierbei um eine Anwendung handelt, welche innerhalb eines Produktionzykluses erfolgen muss. Deshalb ist es sinnvoll, die Inferenz des KI-Modells auf dem Edge-Steuergerät auszuführen. Dazu ist neben dem Inferenzergebnis ebenfalls die Positionsinformationen des Roboters erforderlich, sodass der Robotersteuerung zur Ermittlung der Position eine Aufnahmefunktion zugewiesen wird. Durch die Kombination der Positionsinformationen des Roboters und der Ergebnisse der Inferenz, also der in den Bilddaten lokalisierten Fehlstellen, werden neue Fahraufträge zur punktuellen Nacharbeitung der Fehlstellen erzeugt. Dies erfolgt in der Nachverarbeitungsfunktion des Edge-Steuergerätes, welchem neben dieser Funktion auch eine Inferenz- sowie dieselbe Vorverarbeitungsfunktion wie der Cloud zugeordnet wird. Zur Dokumentation und Nachweisbarkeit der Produktqualität durch die bereits erwähnte eindeutige Zuordnung der lokalisierten Fehlstellen und der durchgeführten Nachbearbeitung zur entsprechenden Glasscheibe, ist die Kommunikation zwischen dem RFID-Reader und dem Edge-Steuergerät erforderlich. Das vollständige Systemmodell ist in ABBILDUNG 3 dargestellt.

V. DISKUSSION

Das Beschreibungsmittel definiert eine Symbolik und Regeln, welche leicht interdisziplinär verstanden werden können. Dies zeigte sich bei der Modellierung der beiden Anwendungsfälle. Die vorgestellte Methodik zur Modellierung entlang der Ebenen förderte zusätzlich das interdisziplinäre Verständnis (A1).

Über die definierte Symbolik sind die KI-Komponenten, die Anlagenstruktur und der Prozess darstellbar und die Modellierung wird auf die relevanten Elemente begrenzt. (A2)

Durch die Verbindung von technischen Ressourcen über Kommunikationsverbindungen, die Zuweisung von Software zu technischen Ressourcen und die Zuweisung von technischen Ressourcen zu Prozessschritten werden die wechselseitigen Abhängigkeiten darstellbar. Wird beispielsweise im ersten Anwendungsfall der Lagesensor getauscht, ist sofort ersichtlich, dass die KI-Anwendung durch Wegfall einer Aufnahmefunktion betroffen ist. Oder wird beispielsweise im zweiten Anwendungsfall die Software der Robotersteuerung aktualisiert, so ist direkt erkennbar, dass die Automatisierungs- und Aufnahmefunktion sowie die Kommunikationsverbindungen zum Edge-Gerät oder zur Auftragseinheit betroffen sein könnten. (A3)

Das Beschreibungsmittel ermöglicht die Modellierung von unterschiedlichen KI-Softwarearchitekturen, weil die KI-Funktionen beliebigen technischen Ressourcen in Abhängigkeit der Systemanforderungen zugewiesen werden können. Beispielsweise wurden in den Anwendungsfällen zwei unterschiedliche Architekturen modelliert. Im ersten Anwendungsfall wird eine Cloud-Architektur und im zweiten Anwendungsfall eine Hybridform aus Cloud- und Edge-Architektur verwendet. (A4)

Die Methodik des Beschreibungsmittels unterstützt CRISP-DM in den ersten Schritten bei der Problemformulierung und in den späteren bei der Lösungsfindung und Dokumentation. Die einfache Darstellung hilft dabei, ein domänenübergreifendes Systemverständnis aufzubauen und ermöglicht die Verteilung der Aufgaben an die einzelnen Beteiligten entlang des CRISP-DM. (A5)

Die Schnittstellen zwischen den Funktionen sowie die Verteilung der Software auf die Hardware sind für alle Beteiligten erkennbar. Die Dokumentation auf Systemebene erleichtert die Integration und langfristige Wartung im Anlagen-Lebenszyklus.

In der aktuellen Form des Beschreibungsmittels können keine zeitlichen Abhängigkeiten erfasst werden. Zum Beispiel, dass die Datenvorverarbeitung vor der Inferenz ausgeführt werden muss. Aktuell besteht auch noch keine Möglichkeit, die einzelnen Systemelemente zu attributieren. Dadurch könnten wichtige Systemattribute, wie beispielsweise die Kommunikationsgeschwindigkeit, dokumentiert und dargestellt werden.

VI. Schlussfolgerung

In diesem Beitrag wird ein Beschreibungsmittel zur Modellierung von KI-Anwendungen für Automatisierungssysteme vorgestellt. Das Beschreibungsmittel erlaubt es, KI-Anwendungen für Automatisierungssysteme interdisziplinär und leicht verständlich zu modellieren. Dafür wird eine Symbolik sowie Regeln zur Kombination der Symbole und eine Semantik definiert. Das Beschreibungsmittel besteht aus Funktionen, technischen Ressourcen und Produkten, welche über Kommunikationsbeziehungen, Zuweisungen oder Material- und Energieflüsse miteinander verbunden werden. Dadurch wird es möglich, die Anlagenstruktur, die KI-Komponenten und den dazugehörigen Prozess inklusive der wechselseitigen Abhängigkeiten grafisch darzustellen, auch für unterschiedliche KI-Systemarchitekturen. Die Schnittstellen zwischen den Elementen sowie die Verteilung der Software auf die Hardware sind für alle Beteiligten direkt ersichtlich. Dadurch wird ein interdisziplinärer Kommunikationsrahmen für domänenübergreifende Zusammenarbeit bereitgestellt, welcher die Kommunikation fördert und die Lösung auf verständliche Art und Weise dokumentiert. Das Beschreibungsmittel kann begleitend zu den etablierten Vorgehensmodellen wie CRISP-DM eingesetzt werden, um den Mehraufwand durch die Modellierung gering zu halten.

Insgesamt bietet die Modellierung auf Basis dieses Beschreibungsmittels das Potenzial, die Entwicklung, die Integration, den Betrieb sowie die Wartung von KI-Anwendungen im Anlagen-Lebenszyklus zu erleichtern.

VII. Ausblick

Im nächsten Schritt wird das Beschreibungsmittel um ein Informationsmodell ergänzt. Mithilfe des Informationsmodells können Funktionen, wie beispielsweise die Datenvorverarbeitung, systematisch in Form von Softwarekomponenten gekapselt und damit wiederverwendbar gemacht werden. Ein Beispiel für die Kapselung von Softwarekomponenten in Kombination mit einer grafischen Modellierung liefert die *Business Process Model and Notation* (BPMN) [31]. Außerdem könnten auf Basis eines Informationsmodells verschiedene Attribute für die modellierten Komponenten hinterlegt werden, welche beispielsweise automatisierte Konsistenzprüfungen erlauben würden. Ein weiterer Schritt könnte die Entwicklung und Bereitstellung von Entwurfsmustern für häufig auftretende Anwendungsfälle sein. Dadurch könnte der Entwicklungsaufwand von KI-Anwendungen weiter reduziert werden. Außerdem ist geplant, das Beschreibungsmittel in ein Werkzeug zu integrieren. Ein Beispiel für ein Web-basiertes Werkzeug wird von [32] für die formalisierte Prozessbeschreibung unter https://demo.fpbjs.net/ gegeben. Wie auch in [32] könnten Assistenzfunktionen in das Werkzeug integriert werden, welche den Anwender bei der Modellierung unterstützen.

Danksagung

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr – Projekt EKI.

Literatur

[1] Bundesministerium für Wirtschaft und Energie (BMWi), *Wegweiser Industrie 4.0: Orientierung, Anwendungsbeispiele, Handlungsempfehlungen*, 2020.

[2] Forschungsbeirat der Plattform Industrie 4.0 / acatech - Deutsche Akademie der Technikwissenschaften, *Industrie 4.0 – Forschung für die Gestaltung der Zukunft: Impulsbericht des Forschungsbeirats der Plattform Industrie 4.0*, 2021.

[3] R. S. Peres, X. Jia, J. Lee, K. Sun, A. W. Colombo, and J. Barata, “Industrial Artificial Intelligence in Industry 4.0-Systematic Review, Challenges and Outlook,” *IEEE Access*, vol. 8, pp. 220 121–220 139, 2020.

[4] Bundesministerium für Wirtschaft und Energie (BMWi), *Auf Künstliche Intelligenz kommt es an: Beitrag von KI zur Innovationsleistung und Performance der deutschen Wirtschaft*, 2020.

[5] D. Sculley, G. Holt, D. Golovin, E. Davydov, T. Phillips, D. Ebner, V. Chaudhary, M. Young, J.-F. Crespo, and D. Dennison, "Hidden Technical Debt in Machine Learning Systems," *Advances in Neural Information Processing Systems*, vol. 28, 2015.

[6] M. W. Hoffmann, R. Drath, and C. Ganz, "Industrielle Anforderungen an Künstliche Intelligenz-Lösungen," in *Automation 2020*, ser. VDI-Berichte. Düsseldorf: VDI Verlag, 2020, pp. 617–628.

[7] C. Kaymakci, S. Wenninger, and A. Sauer, "A Holistic Framework for AI Systems in Industrial Applications," in *Innovation Through Information Systems*, ser. Lecture Notes in Information Systems and Organisation, F. Ahlemann, R. Schütte, and S. Stieglitz, Eds. Cham: Springer International Publishing, 2021, vol. 47, pp. 78–93.

[8] C. Schröer, F. Kruse, and J. Marx Gómez, "A Systematic Literature Review on Applying CRISP-DM Process Model," *Procedia Computer Science*, vol. 181, pp. 526–534, 01 2021.

[9] J. S. Saltz, "CRISP-DM for Data Science: Strengths, Weaknesses and Potential Next Steps," in *2021 IEEE International Conference on Big Data (Big Data)*. IEEE, 12/15/2021 - 12/18/2021, pp. 2337–2344.

[10] Forschungsbeirat der Plattform Industrie 4.0 / acatech - Deutsche Akademie der Technikwissenschaften, *Modellierung- und Simulationsbedarfe der intelligenten Fabrik: Expertise des Forschungsbeirats der Plattform Industrie 4.0*, 2021.

[11] R. Haberfellner, O. de Weck, E. Fricke, and S. Vössner, *Systems Engineering*. Cham: Springer International Publishing, 2019.

[12] Verein Deutscher Ingenieure e.V., "Einordnung und Bewertung von Beschreibungsmitteln aus der Automatisierungstechnik," Oktober 2005.

[13] E. Schnieder, *Methoden der Automatisierung*. Wiesbaden: Vieweg+Teubner Verlag, 1999.

[14] C. P. Filho, E. Marques, V. Chang, L. Dos Santos, F. Bernardini, P. F. Pires, L. Ochi, and F. C. Delicato, "A Systematic Literature Review on Distributed Machine Learning in Edge Computing," *Sensors (Basel, Switzerland)*, vol. 22, no. 7, 2022.

[15] P. Winzer, *Generic Systems Engineering*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2016.

[16] F. Martinez-Plumed, L. Contreras-Ochando, C. Ferri, J. Hernandez-Orallo, M. Kull, N. Lachiche, M. J. Ramirez-Quintana, and P. Flach, "CRISP-DM Twenty Years Later: From Data Mining Processes to Data Science Trajectories," *IEEE Transactions on Knowledge and Data Engineering*, vol. 33, no. 8, pp. 3048–3061, 2021.

[17] R. Wirth and J. Hipp, "CRISP-DM: Towards a standard process model for data mining," *Proceedings of the 4th International Conference on the Practical Applications of Knowledge Discovery and Data Mining*, 01 2000.

[18] S. Huber, H. Wiemer, D. Schneider, and S. Ihlenfeldt, "DMME: Data mining methodology for engineering applications – a holistic extension to the CRISP-DM model," *Procedia CIRP*, vol. 79, pp. 403–408, 2019.

[19] S. Studer, B. Bui, C. Drescher, A. Hanuschkin, L. Winkler, S. Peters, and K.-R. Müller, "Towards CRISP-ML(Q): A Machine Learning Process Model with Quality Assurance Methodology," *Machine Learning and Knowledge Extraction*, vol. 3, pp. 392–413, 04 2021.

[20] S. Amershi, A. Begel, C. Bird, R. DeLine, H. Gall, E. Kamar, N. Nagappan, B. Nushi, and T. Zimmermann, "Software Engineering for Machine Learning: A Case Study," in *2019 IEEE/ACM 41st International Conference on Software Engineering: Software Engineering in Practice (ICSE-SEIP)*, 2019, pp. 291–300.

[21] C. J. Costa and J. T. Aparicio, "POST-DS: A Methodology to Boost Data Science," in *2020 15th Iberian Conference on Information Systems and Technologies (CISTI)*. IEEE, 2020.

[22] F. Plumed, L. Contreras-Ochando, C. Ferri, P. Flach, J. Hernandez-Orallo, M. Kull, N. Lachiche, and M. Ramírez-Quintana, "CASP-DM: Context Aware Standard Process for Data Mining," 09 2017.

[23] J. Pfrommer, C. Frey, L. Wessels, and J. Beyerer, "ML4P: Ein Standard-Vorgehensmodell für die Anwendung Maschinellen Lernens in der industriellen Produktion," in *Automation 2020*, ser. VDI-Berichte. Düsseldorf: VDI Verlag, 2020, pp. 629–644.

[24] NAMUR Interessengemeinschaft Automatisierungstechnik der Prozessindustrie e.V, "NAMUR Open Architecture (NOA): NOA Konzept," 2020.

[25] M. Seidl, M. Scholz, C. Huemer, and G. Kappel, *UML @ Classroom*. Cham: Springer International Publishing, 2015.

[26] T. Weilkiens, *Systems Engineering mit SysML/UML: Anforderungen, Analyse, Architektur*, 3rd ed. Heidelberg: dpunkt.verl., 2014.

[27] Verein Deutscher Ingenieure e.V., "Formalisierte Prozessbeschreibungen," September 2005.

[28] A. Fay, C. Diedrich, M. Dubovy, C. Eck, C. Hildebrandt, A. Scholz, T. Schröder, and R. Wiegand, *Abschlussbericht - SemAnz40: Vorhandene Standards als semantische Basis für die Anwendung von Industrie 4.0*. Hamburg: Helmut-Schmidt-Universität Universität der Bundeswehr Hamburg, 2017.

[29] A. Roth, Ed., *Einführung und Umsetzung von Industrie 4.0: Grundlagen, Vorgehensmodell und Use Cases aus der Praxis*. Berlin and Heidelberg: Springer Gabler, 2016.

[30] T. Meudt, M. Pohl, and J. Metternich, "Die Automatisierungspyramide - Ein Literaturüberblick," 2017.

[31] Object Management Group, "Business Process Model and Notation (BPMN)," 12/2013.

[32] H. Nabizada, A. Köcher, C. Hildebrandtand, and A. Fay, "Offenes, webbasiertes Werkzeug zur Informationsmodellierung mit Formalisierter Prozessbeschreibung," in *Automation 2020*, ser. VDI-Berichte. Düsseldorf: VDI Verlag, 2020.

Anforderungen an eine Engineering-Plattform für die KI-basierte Automation

René Heesch*, Julian Putzke*, Simon Althoff‡, Philip Topalis*, Marvin Schieseck*,
Alexander Fay*, Oliver Niggemann*
*Institut für Automatisierungstechnik
Helmut Schmidt Universität
Hamburg, Deutschland
Email: rene.heesch@hsu-hh.de
‡ Weidmüller Interface GmbH & Co. KG
Detmold, Deutschland
Email: simon.althoff@weidmueller.com

***Zusammenfassung*—Das Engineering von Applikationen der künstlichen Intelligenz (KI) für Automatisierungssysteme ist eine domänenübergreifende Tätigkeit, welche in besonderer Weise das Zusammenbringen der Welt der Softwareentwicklung und der Welt der Automatisierungstechnik erfordert. Erschwerend kommt hinzu, dass die Automatisierungshardware zumeist nur mit einer herstellerabhängigen Software konfiguriert werden kann. Eine herstellerunabhängige und quelloffene Lösung, welche einerseits das Engineering von Automatisierungslösungen und korrespondierende KI-Applikationen ermöglicht und andererseits die Automation durch software-integrierte Assistenzfunktionen für die KI-Services unterstützt, existiert bisher nicht. Im dtec.bw-Projekt EKI wird dieses Problem adressiert und eine Engineering-Plattform für die einfache Integration von KI-Applikationen und mit KI-basierten Assistenzfunktionen entwickelt. In diesem Beitrag werden die Anforderungen an eine solche herstellerunabhängige und quelloffene Engineering-Plattform aufgezeigt. In diesem Zuge wird ebenfalls analysiert, welche bestehenden Lösungen diese Anforderungen adressieren und vorgestellt, wie die Anforderungen bei der Konzeptionierung dieses neuen Engineeringansatzes umgesetzt werden sollen.**

***Index Terms*—CPPS, Engineering, KI-Integration, Automatisierung, Engineering-Plattform**

I. Einleitung

Im heutigen Produktionsumfeld sehen sich Unternehmen zunehmend mit immer häufiger variierenden Produktanforderungen und damit immer kleiner werdenden Losgrößen konfrontiert [1]. Dies hat zu einem Bedarf an neuen adaptiven und veränderbaren Produktionsanlagen sowie den dazugehörigen Automatisierungslösungen geführt. Gerade das Engineering, also das Anpassen der Automatisierungslösung durch Experten, hat sich in diesem Zusammenhang als Engpass erwiesen. Als Cyber-physische Produktionssysteme (CPPS) bezeichnet man eine Klasse von Produktionssystemen, die für schnelle Anpassungen an veränderte Anforderungen und Bedingungen besonders geeignet sind. Sie bestehen in der Regel aus unterschiedlichen Modulen, die wiederum an variierende Rahmenbedingungen angepasst und miteinander kombiniert werden können. Mit ihrem autonomen und kooperativen Verhalten auf allen Produktionsebenen unterscheiden sie sich signifikant von traditionellen, hierarchischen Automationsstrategien [2]. Um die Interoperabilität innerhalb der CPPS und mit anderen Systemen zu gewährleisten, müssen Informationen über die Systeme maschinenlesbar dargestellt werden. In diesem Zusammenhang wird die Nutzung von semantischen Beschreibungsmitteln, wie beispielsweise Ontologien, untersucht [3]. So können die Funktionen von einzelnen Ressourcen innerhalb der CPPS als abstrakte Beschreibung in Form von *Fähigkeiten* dargestellt werden. Die Implementierung der entsprechenden Fähigkeiten, mit Hilfe derer die Fähigkeit von dem Modul beschrieben und aufgerufen werden kann, wird hingegen als *Skill* bezeichnet [4]. Ein solches Produktionssystem ermöglicht die Nutzung von neuen Automationsansätzen, die auf symbolischen und subsymbolischen Methoden der Künstlichen Intelligenz (KI) basieren [5]. Des Weiteren spielen Methoden der KI in der Produktion im Allgemeinen eine immer bedeutendere Rolle und gehören in vielen Bereichen der Produktion zum Stand der Technik. So können Methoden der KI beispielsweise sowohl für das Überwachen des Maschinenzustandes und das Optimieren von Wartungsintervallen in Form von *Predictive Maintenance* oder für die optische Überwachung der Produktqualität in Form von *automatischer optischer Inspektion* genutzt werden. Für das Auswählen und das Konfigurieren des passenden Ansatzes wird jedoch in der Regel Expertenwissen benötigt. Des Weiteren erfolgt die Integration einer KI-Komponente im Produktionssystem zurzeit nachgelagert und nicht direkt im Prozess des Engineerings, was die Kommunikation mit dem Automationssystem erschwert.

Engineering-Plattformen, welche sich alleine mit der Programmierung von Automatisierungslösungen (z.B. SPS) beschäftigen, fehlt die Funktionalität für die Integration und Anwendung von KI-basierten Assistenzfunktionen sowie die Integration von KI-Anwendungen. Stattdessen gibt es eine Vielzahl von Plattformen der unterschiedlichen Hersteller von Automatisierungshardware. Diese Plattformen können häufig lediglich für das Engineering der zugehörigen Hardware genutzt werden [6].

Aus diesem Grund wird im Rahmen des DTEC-Projektes 'EKI - Engineering für die KI-basierte Automation in virtuellen und realen Produktionsumgebungen' in Zusammenarbeit

https://doi.org/10.24405/14546

mit dem Projektpartner Weidmüller Interface GmbH & Co. KG eine offene und erweiterbare Engineering-Plattform entwickelt. Diese Engineering-Plattform soll sowohl Echtzeit- wie Nicht-Echtzeit-KI-Applikationen ausführen können. Zudem soll die Engineering-Plattform über KI-basierte Assistenzfunktionen verfügen, die den Anwender bei der Auswahl und Integration von KI-Algorithmen sowie bei der Ablaufplanung und Parametrisierung unterstützen. So soll beispielsweise eine Assistenzfunktion entwickelt werden, die automatisiert eine Sequenz von parametrisierten Skill-Aufrufen erstellen kann. Diese greift dabei auf KI-basierte Planungsansätze zurück und nutzt als Input die Fähigkeitsbeschreibungen der zur Verfügung stehenden Module und stellt fest, welche Module eines CPPS mit welchen Parametersätzen benötigt werden, um ein gewünschtes Produkt herzustellen. Die Sequenz von Skill-Aufrufen kann anschließend von einer übergeordneten Steuerung ausgeführt werden, welche von den betreffenden Modulen den entsprechenden Skill aufruft. Anlässlich der Erweiterbarkeit der Plattform soll es zudem möglich sein, weitere Assistenzfunktionen in die Plattform einzubringen.

Im Rahmen dieses Beitrages werden in einem ersten Schritt die Anforderungen an eine Engineering-Plattform definiert, welche für die Integration von KI-Komponenten im Engineering geeignet ist und eine Erweiterung von KI-basierten Assistenzfunktionen zulässt. Im Anschluss erfolgt eine Betrachtung des Standes der Technik hinsichtlich der Anforderungen. Abschließend wird ein Konzept für die zu entwickelnde Plattform sowie die geplante Validierung anhand einer Realanlage vorgestellt.

II. Anforderungen

Im Rahmen des Projektes wurden verschiedene Anforderungen an eine offene und KI-integrierbare Engineering-Plattform identifiziert. Speicherprogrammierbare Steuerungen (SPS) sind ein elementarer Bestandteil heutiger Automatisierungssysteme [7]. Es existiert eine Vielzahl unterschiedlicher SPS-Hersteller. Obwohl es den IEC61131 Standard für das Programmieren von Steuerungen gibt, nutzt der Großteil der Hersteller eine eigene Ausprägung der Sprache. Dies hat zur Folge, dass für das Programmieren der Steuerungen von unterschiedlichen Herstellern in der Regel auch jeweils eine herstellerabhängige integrierte Entwicklungsumgebung (IDE) benötigt wird, für die ein Nutzer oft zusätzliche Lizenzgebühren entrichten muss [6]. Zudem erhöht sich der Druck auf produzierende Unternehmen, flexibler zu werden und ihre Produktionssysteme, beispielsweise aufgrund sich wandelnder Kundenanforderungen, schneller anpassen zu können, um wettbewerbsfähig zu bleiben [1]. Die beschriebene Vielzahl von unterschiedlicher Engineering-Software, die auf dem Gerät des Automatisierungsingenieurs installiert werden muss, und jeweils nur für ausgewählte Steuerungen des Maschinenparks verwendet werden kann, steht der schnellen Anpassung der Automatisierung jedoch im Wege. Daraus leiten sich folgende Anforderungen an eine offene und KI-fähige Engineering-Plattform ab:

Anforderung 1: Mithilfe der Plattform muss das Engineering unabhängig vom Hersteller einer Steuerung möglich sein.

Anforderung 2: Die Engineering-Plattform muss innerhalb kurzer Zeit und ohne komplexe Lizenzmodelle auf dem Gerät des Automatisierungsingenieurs einsatzbereit sein.

Aufgrund der Komplexität der zu automatisierenden Prozesse verfügen moderne Produktionsanlagen in der Regel über mehr als eine SPS. Neben den konventionellen Kommunikationsschnittstellen für die Kommunikation zwischen einzelnen Hardwarekomponenten der Automatisierung existieren ebenfalls Standards für den Datenaustausch zwischen Geräten unterschiedlicher Hersteller, wie die OPC Unified Architecture (OPC UA).

Anforderung 3: Für das Engineering von komplexen Automatisierungssystemen ist es notwendig, dass die Engineering-Plattform das Konfigurieren gängiger Kommunikationsschnittstellen unterstützt.

Ein weiterer Trend, mit dem ein Automatisierungsingenieur im heutigen Produktionsumfeld konfrontiert wird, ist der zunehmende Einsatz von Methoden der KI in der Produktion. So stellte das Bundesministerium für Wirtschaft und Energie bereits 2020 fest, dass KI in der Produktion eine intelligente Automatisierung von Prozessen, beispielsweise mithilfe von Predictive Maintenance (PM), erlaubt [8]. PM bezeichnet dabei die vorausschauende Wartung von Anlagen. Anders als bei einer Wartung in festen Intervallen, wird hier mit Hilfe Methoden der KI, basierend auf Maschinen- und Prozessdaten, der optimale Zeitpunkt für eine Wartung bestimmt [9]. PM ist dabei nur eine mögliche Anwendung von Methoden der KI in der Produktion. So ist auch die Nutzung von Bildverarbeitungsmethoden für die Qualitätsüberwachung und Identifikation in der Fertigung beispielsweise ein gängiges Mittel in der Automobilindustrie [10].

Anforderung 4: Mithilfe der Engineering-Plattform muss es möglich sein, KI-Anwendungen zu konfigurieren und diese im Engineering automatisierter Anlagen zu integrieren.

Insbesondere, aber nicht ausschließlich, subsymbolische Methoden aus dem Bereich des Maschinellen Lernens (ML) bergen dabei besondere Herausforderungen für die Integration. Das Ziel von ML-Algorithmen ist das Erkennen von Mustern und Gesetzmäßigkeiten in Datensätzen. Zu diesem Zweck müssen die entsprechenden Datensätze in ausreichender Qualität und Quantität vorliegen. In Abhängigkeit des Algorithmus wird anschließend auf Basis der vorliegenden Daten ein ML-Modell trainiert. Die Anwendung des trainierten Modells auf neue Daten wird als Inferenz bezeichnet [9]. Da eine SPS nicht für das Ablegen größerer Datenmengen geeignet ist, führt dies zu einer weiteren Anforderung:

Anforderung 5: Innerhalb der Engineering-Plattform muss eine Anbindung der SPS an eine Cloud für die Datenspeicherung ermöglicht werden. In diesem Zuge muss es ebenfalls möglich sein, die Datenspeicherung zu konfigurieren, um neben den zu speichernden Daten ebenfalls die Abtastrate jedes Parameters festzulegen.

Für das Training des ML-Modells muss außerdem ausreichend Rechenleistung zur Verfügung stehen. Der Rechenaufwand ist dabei von dem geplanten Anwendungsfall und dem ausgewählten Algorithmus abhängig. Allerdings reicht die Leistungsfähigkeit der Steuerungen für die Berechnung von aufwendigen Algorithmen nicht aus [11]. Ebenfalls in Abhängigkeit des Anwendungsfalls und des Algorithmus muss die Inferenz entweder vor Ort auf der Steuerung oder in der Cloud ausgeführt werden. Dies führt zu zwei weiteren Anforderungen:

Anforderung 6: Es muss aus der Engineering-Plattform möglich sein, das Training und die Anwendung von KI-Algorithmen in der Cloud zu konfigurieren, damit jederzeit genug Rechenressourcen für die Umsetzung von KI-Algorithmen zur Verfügung stehen.

Anforderung 7: Innerhalb der Engineering-Plattform muss es möglich sein, trainierte Modelle aus der Cloud zu exportieren und auf der SPS zu deployen, damit die Inferenz auf der SPS erfolgen kann.

Neben der Integration von KI-Algorithmen im Engineering von Produktionsanlagen existieren ebenfalls Ansätze, mit Hilfe von symbolischen oder subsymbolischen Methoden der KI das Engineering automatisierter Anlagen an sich zu erleichtern. Diese Assistenzfunktion betrifft das Programmieren der Automatisierungslösung, z.B. unter Nutzung der IEC61131. Hier soll die Möglichkeit geschaffen werden, dass eine in die Engineering-Lösung integrierte KI-basierte Assistenzfunktion dem Automatisierungsingenieur Vorschläge für die Programmierung von Anlagen anbietet. Diese sind zum Großteil jedoch noch Stand der Forschung und können noch nicht in der Breite angewendet werden. Dennoch sollten grundsätzlich neue Ansätze, die den Automatisierungsingenieur beim Engineering unterstützen, in der Engineering-Plattform integriert und somit der Plattform neue Funktionalitäten hinzugefügt werden können.

Anforderung 8: Es muss möglich sein, die Engineering-Plattform zu erweitern und beispielsweise mit KI-basierten Assistenzfunktionen auszustatten, welche ebenfalls auf alle, zur Verfügung stehenden Schnittstellen zugreifen können.

III. Stand der Technik

Im Folgenden werden aktuelle Entwicklungen und Lösungen im Zusammenhang mit den definierten Anforderungen an Engineering-Plattformen vorgestellt.

Mit der Einführung der SPS wurden von verschiedenen Herstellern unterschiedliche Laufzeitumgebungen und Programmiersprachen für ihre Hardware entwickelt. Um die dadurch entstanden Komplexität für die Nutzer zu reduzieren, wurde von der International Electronical Commision der IEC61131 Standard ausgearbeitet, mithilfe derer die Wiederverwendung von Code erleichtert werden soll. Für die Wiederverwendung von Code ist es jedoch zusätzlich notwendig, dass die Informationen, die auf der einen SPS programmiert wurden, auf andere SPS übertragen werden können und das Programm dieselben Funktionen aufweist wie zuvor. Um dieses Problem zu adressieren, wurde vom PLCopen Technical Committee 6 ein erweiterbares XML-Interface definiert. PLCopen ist eine Organisation, die Standards im Bereich der industriellen Steuerungstechnik definiert, durch deren Anwendung die Effizienz bei der Entwicklung und Wartung von industrieller Softwareapplikationen gesteigert werden soll. Das Ziel des XML-Interfaces ist das Übertragen von Programmcode, vollständigen Projekten oder benutzerdefinierten Funktionsblöcken von einer Entwicklungsumgebung in eine andere [12].

Mit der Weiterentwicklung der Hardware und der zunehmenden Komplexität der Programme, die durch die Hardware ausgeführt werden kann, wurden auch die integrierte Entwicklerumgebungen (IDEs) zum Entwickeln der Programme deutlich komplexer. Dies führt wiederum zu einem erhöhten Aufwand für die Installation der entsprechenden Software. Eine Möglichkeit, dies Problem zu umgehen, bieten web-basierte IDEs. Im Vergleich zu einer IDE, welche lokal auf dem Gerät des Anwenders installiert ist und dann auch nur dort verwendet werden kann, bietet eine web-basierte IDE die Flexibilität, auf nahezu jedem Gerät ohne Installation verwendbar zu sein. Der Benutzer muss lediglich einen Browser öffnen und sich über den entsprechenden Server mit der web-basierten IDE verbinden und kann anschließend in dieser arbeiten [13].

Aufgrund der zunehmenden Bedeutung von KI-Methoden im industriellen Umfeld gewinnt auch die Art und Weise, wie diese im Engineering integriert werden können, zunehmend an Bedeutung. Ein integrierter Ansatz, für die direkte Erstellung und Anbindung von KI-Algorithmen im Engineering einer vollautomatisierten Anlage, existiert zurzeit nicht. So sind Lösungen vorhanden, welche in erster Linie das Ausführen von KI-Anwendungen fokussieren. Hierbei wird gängigerweise die KI-Anwendung auf ein Maschinen- oder Prozessdatenbasierten Maschine-Learning-Ansatz (ML-Ansatz) reduziert. Das typische Vorgehen ist die Einbindung von Datensammlern in die Fertigung, um Datensätze für das Trainieren und Validieren der zu erzeugenden Modelle zu generieren. Diese Datensätze werden dann in gängigen Frameworks wie PyTorch, TensorFlow, SciKit-Learn® genutzt, um Modelle zu erzeugen. Hierdurch ergeben sich kaum Einschränkungen, wo die Daten gespeichert oder die Modelle trainiert werden. Allerdings erfolgt die Datensammlung durch manuelle Konfiguration und muss für die Inferenz auf einer SPS erneut durchgeführt werden. Durch die Anwendung außerhalb einer Engineering-Plattform fallen allerdings Synergien weg, da Schnittstellen mehrfach angebunden oder Datenflüsse wiederkehrend manuell angelegt werden müssen [14].

Eine Möglichkeit zum Erstellen der benötigten Datenflüsse bieten sogenannte Datenfluss-orientierte (dataflow) Programme. Sie wurden entwickelt, da viele Industrieanwendungen die Integration von Online-Services und nahezu Echtzeitanwendung benötigen. Obwohl dies auch mit herkömmlichen Tools möglich ist, kann die Umsetzung hinsichtlich der Erstellung und Verknüpfung von Datenverarbeitungsschritten, APIs, zeitaufwendig sein [15]. Dataflow Programme, wie NodeRed oder WoTKit Processor, bieten eine Lösung für dieses Problem. Sie verfügen über grafische Oberflächen, in denen gekapselte Softwareobjekte miteinander verbunden und ausgeführt werden können. Nodes stellen dabei Dateninputs, Datenoutputs oder Funktionen dar, während Pfeile die Nodes verbinden und den Datenfluss dazwischen bestimmen. NodeRed ist ein webbasiertes Tool, dass den Fokus auf die Konnektivität zwischen der Hardware und den APIs setzt. Zudem ist es ein offenes Tool, was von der Erweiterung der Community profitiert.

Bezüglich der Ausführung von trainierten KI-Modellen bestehen heute schon Lösungen, die das Ausführen der Inferenz sowohl in Echtzeit als auch Nicht-Echtzeit ermöglichen. Die nicht-Echtzeit-fähigen Applikationen dominieren zurzeit deutlich, da ML-Algorithmen typischerweise nicht für Latenz-kritische Anwendungen und damit als Eingangsgröße in Automatisierungsprogrammen genutzt werden. KI-Modelle, welche tiefe neuronale Netze nutzen, z.B. für die optische Inspektion nach einem Fertigungsschritt, benötigen deutlich länger als die Zykluszeit der Steuerung. Die trainierten KI-Modelle können auf der Steuerung ausgeführt werden und nach der Berechnung des Modells können beispielsweise fehlerhafte Werkstücke aus der Fertigung ausgeschleust oder nachbearbeitet werden. Hierfür stehen typischerweise aber mehrere Sekunden zur Verfügung [16]. Um Einschränkungen von KI- bzw. ML-Frameworks zu umgehen, setzt sich die Nutzung von ONNX als Beschreibungsstandard für KI-Anwendungen durch. ONNX beschreibt die mathematischen Operationen zwischen Eingangs- und Ausgangsdaten der ML-Modelle und entkoppelt somit die KI-Engineeringumgebung von der Ausführung des KI-Modells.

In gängigen Lösungen von Automatisierungsanbietern wird das Erlernen von KI-Anwendungen allein dem Können und der Kreativität des Automatisierungsexperten oder des Data Scientists überlassen. Typischerweise fehlt dem SPS-Programmierer das nötige Wissen in Bezug auf Maschinelle Lernverfahren und die Erfahrung in Bezug auf die Nutzung von KI-Engineering-Umgebungen. Der Data Scientist erstellt typischerweise ohne Domänenwissen in Bezug auf Automatisierungstechnik Modelle rein anhand der aufgezeichneten Daten [17].

Dies macht die Notwendigkeit deutlich, dass neben der reinen Integration von KI-/ML-Anwendungen in die Automatisierung eine Unterstützung notwendig ist, um effizient ML-Modelle zu erstellen, auf eine Steuerung zu integrieren und anzuwenden. Daher sind Assistenzfunktionen ein essenzieller Teil einer KI-basierten Automation, da diese auf unterschiedlichste Weise den Automatisierungsingenieur über den KI-Anwendungs-Lebenszyklus unterstützen können.

IV. Konzept

Nachdem der Stand der Technik mit Blick auf die definierten Anforderungen an eine KI-integrierte Engineering-Plattform vorgestellt wurde, wird in diesem Abschnitt konzeptionell die geplante Umsetzung der Plattform im Projekt EKI vorgestellt.

Um den Zugriff auf die Steuerung gemäß der ersten Anforderung zu gewährleisten, wird im Rahmen des Projektes PLC Open und dessen Erweiterungen genutzt, da es sich um eine hersteller- und produktneutrale Schnittstelle handelt. Für das EKI Projekt sind beispielsweise PLCopen Communication und PLCopen XML Exchange relevant. PLC Communications standardisiert die Nutzung von OPC UA in Kombination mit PLCopen und PLCopen XML Exchange erlaubt es, Programme, Bibliotheken und Projekte zwischen Entwicklungsumgebungen auszutauschen.

Anforderung zwei fordert eine kurzfristige Einsatzbereitschaft der Plattform auf dem Gerät des Automatisierungsingenieurs. Der Großteil der marktrelevanten Anbieter macht es notwendig, dass der Automatisierungsingenieur eine proprietäre Software auf dem Endgerät installiert, was insbesondere bei der Versionierung zu Schwierigkeiten führen kann. Eine Alternative hierzu ist eine web-basierte Engineering-Plattform, bei der der Zugriff über den Browser erfolgt. Die Engineering-Plattform kann dabei sowohl auf der Steuerung als auch in der Cloud gehostet werden. Dadurch muss der Bediener lediglich die IP-Adresse oder die Cloud URL im Browser angeben und kann so ohne Installationsaufwand oder speziellen Lizenzanforderungen darauf zugreifen.

Als Kommunikationsschnittstelle wurde sich für verschiedene Standards entschieden und somit auch Anforderung 3 erfüllt. Dies betrifft einerseits http(s), Modbus TCP und OPC UA. Allerdings wird in dem Projekt OPC UA priorisiert verwendet, da hier neben der Möglichkeit von verschlüsselter Kommunikation auch ein semantisch beschriebenes Informationsmodell zur Verfügung gestellt wird, was für das Erstellen und Anwenden von KI-Anwendungen ein entscheidender Vorteil ist. Verbreitete Kommunikationsprotokolle wie Modbus TCP werden vor allem für die Datenakquise von Energiemessgeräten verwendet. Energiemessgeräte in unterschiedlicher Messgenauigkeit sind eine häufig genutzte Datenquelle für KI-Anwendungen, da sich Anlagenzustände häufig aus diesen Daten herleiten lassen.

Um KI Anwendung über die Engineering-Plattform zu konfigurieren und diese in die automatisierte Anlage zu integrieren, muss es möglich sein, containerisierte Software zu erstellen und anzuwenden (deployen). Industriell weit verbreitet ist hierbei Docker. Bei dieser Vorgehensweise ist es allerdings wünschenswert, dass hardwareseitig eine Linux Anwendung zur Verfügung steht. Dies bezieht sich insbesondere auf das Deployment von bereits trainierten und containerisierten KI-Anwendungen, welche auf die Rechenleistung der vorgesehenen Steuerung/Hardware abgestimmt sind.

Handelt es sich um Modelle, die komplex, beziehungsweise rechenintensiv sind, werden die Modelle mittels einer virtuellen Maschine in einer frei wählbaren Cloud trainiert. In der Engineering-Plattform soll eine Anbindung an Online Rechenressourcen über NodeRed möglich sein. Es werden hierbei die zur Verfügung gestellten Nodes der jeweiligen Anbieter genutzt. Mithilfe dieses Werkzeugs lassen sich auch Datenflüsse zu den unterschiedlichen Cloudanbietern realisieren. Die dort vorhandenen KI-Engineering-Umgebungen bieten mächtige Werkzeuge, welche die Anforderung fünf bis sieben abdecken können, also die Datenspeicherung, das Training und den Export des Modells.

Die letzte Anforderung betrifft die Erweiterbarkeit der Enginnering-Plattform. Hierzu ist ein AddOn Manager ge-

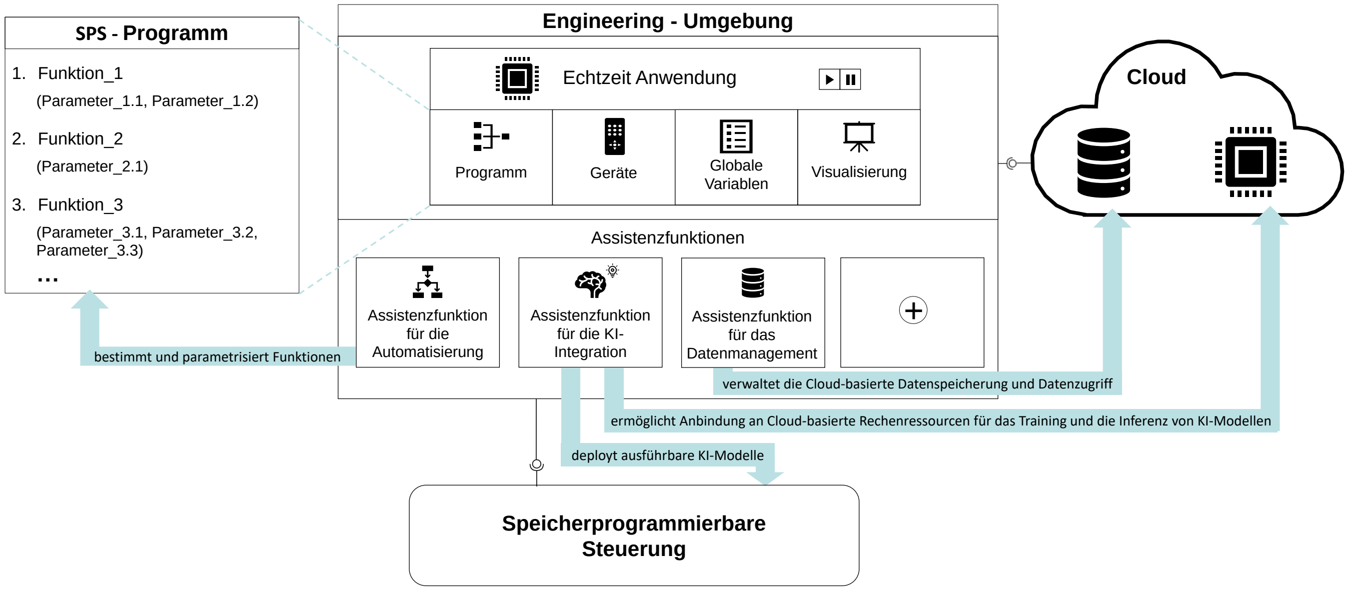


ABBILDUNG 1. DARSTELLUNG DER GEPLANTEN ENGINEERING-PLATTFORM SOWIE DER FUNKTIONSWEISE AUSGEWÄHLTER ASSISTENZFUNKTIONEN

plant, der es dem Anwender ermöglicht, über einen Docker Container seine neue Anwendung oder Assistenzfunktion in der Engineering-Plattform zu integrieren. Die Erweiterung der Plattform durch die Anwender innerhalb einer eigenen Community ist ausdrücklich erwünscht. Daher wird diese auch zum Ende des Projektes unter einer MIT-Lizenz veröffentlicht und so der Community zur Verfügung gestellt.

Eine Darstellung des Konzepts der geplanten Engineering-Plattform sowie der Funktionsweise der geplanten Assistenzfunktionen kann der ABBILDUNG 1 entnommen werden. Im Zentrum steht die Engineering-Plattform von Weidmüller Interface GmbH & Co. KG, die einerseits aus einer Echtzeitumgebung, inklusive SPS-Programm, Geräteverwaltung, Variablendefinition und Visualisierung, und andererseits aus den Assistenzfunktionen/AddOns besteht. Die Plattform ermöglicht eine Anbindung an cloudbasierte Rechenressourcen, sowie die speicherprogrammierbare Steuerung der Anlage.

V. AUSBLICK

Angesichts der zunehmenden Bedeutung von KI in der Industrie wurde im Rahmen des Beitrages analysiert, welche besonderen Anforderungen diese Entwicklung an eine Engineering-Plattform stellt, die für die Integration von KI-Applikationen im Engineering geeignet ist. Außerdem wurde ermittelt, welche Voraussetzungen eine Engineering-Plattform erfüllen muss, damit sie ebenfalls um KI-basierte Assistenzfunktionen erweitert werden kann. Basierend auf den definierten Anforderungen und einem Überblick über den Stand der Technik in diesem Bereich, wurde das Konzept für eine offene, erweiterbare und web-basierte Engineering-Umgebung vorgestellt. Gemäß dem Konzept wird im Rahmen des Forschungsprojektes EKI von der Firma Weidmüller Interfaces GmbH & Co. KG eine Engineering-Plattform entwickelt und anschließend anhand einer Realanlage validiert. Außerdem werden im weiteren Verlauf des Projektes von der Helmut Schmidt Universität KI-basierte Assistenzfunktionen entwickelt, die den Anwender sowohl im Zuge des Engineerings an sich, als auch bei der Auswahl von KI-Applikationen in Abhängigkeit des Anwendungsfalls, unterstützen.

DANKSAGUNG

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt EKI].

LITERATUR

[1] H. Kagermann, J. Helbig, A. Hellinger, and W. Wahlster, *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group*. Forschungsunion, 2013.

[2] L. Monostori, “Cyber-physical Production Systems: Roots, Expectations and R&D Challenges,” *Procedia CIRP*, vol. 17, pp. 9–13, 2014.

[3] G. Fenza, M. Gallo, V. Loia, D. Marino, F. Orciuoli, and A. Volpe, “Semantic CPPS in Industry 4.0,” in *Advanced Information Networking and Applications*, ser. Springer eBook Collection, L. Barolli, F. Amato, F. Moscato, T. Enokido, and M. Takizawa, Eds. Cham: Springer International Publishing and Imprint Springer, 2020, vol. 1151, pp. 1057–1068.

[4] A. Köcher, C. Hildebrandt, L. M. Vieira da Silva, and A. Fay, “A Formal Capability and Skill Model for Use in Plug and Produce Scenarios,” in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, vol. 1, 2020, pp. 1663–1670, ISSN: 1946-0759.

[5] A. Köcher, R. Heesch, N. Widulle, A. Nordhausen, J. Putzke, A. Windmann, and O. Niggemann, “A Research Agenda for AI Planning in the Field of Flexible Production Systems,” in *IEEE International Conference on Industrial Cyber-Physical Systems (ICPS)*, 2022.

[6] V. Vyatkin, “Software engineering in industrial automation: State-of-the-art review,” *IEEE Transactions on Industrial Informatics*, vol. 9, no. 3, pp. 1234–1249, 2013.

[7] W. Bolton, *Programmable logic controllers*. Newnes, 2015.

[8] BMWi, “Auf Künstliche Intelligenz kommt es an: Beitrag von KI zur Innovationsleistung und Performance der deutschen Wirtschaft,” 2020.

[9] A. Mockenhaupt, "Digitalisierung und KI in der Produktion," in *Digitalisierung und Künstliche Intelligenz in der Produktion*. Springer, 2021, pp. 227–269.

[10] M. Kropik, "Produktion," in *Produktionsleitsysteme für die Automobilindustrie*. Springer, 2021, pp. 129–235.

[11] T. Bauernhansl, M. Ten Hompel, and B. Vogel-Heuser, *Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung· Technologien· Migration*. Springer, 2014.

[12] M. Marcos, E. Estevez, F. Perez, and E. Van Der Wal, "XML exchange of control programs," *IEEE Industrial Electronics Magazine*, vol. 3, no. 4, pp. 32–35, 2009.

[13] M. Dutta, K. K. Sethi, and A. Khatri, "Web based integrated development environment," *International Journal of Innovative Technology and Exploring Engineering*, vol. 3, no. 10, pp. 56–60, 2014.

[14] T. Żabiński, T. Maczka, and J. Kluska, "Industrial platform for rapid prototyping of intelligent diagnostic systems," in *Polish Control Conference*. Springer, 2017, pp. 712–721.

[15] M. Blackstock and R. Lea, "Toward a distributed data flow platform for the web of things (distributed node-red)," in *Proceedings of the 5th International Workshop on Web of Things*, 2014, pp. 34–39.

[16] Beckhoff Automation GmbH &amp and Co. KG, Hülshorstweg 20 33415 Verl, "Machine Learning," 24.08.2022. [Online]. Available: https://www.beckhoff.com/de-de/produkte/automation/twincat-3-machine-learning/

[17] M. Lukas, D. Stock, and A. Csiszar, "FabOS: Towards an open, distributed, real-time-capable, and secure operating system for production," *Procedia CIRP*, vol. 104, pp. 962–967, 2021.

Investigating the Use of AI Planning Methods in Real-World CPS Use Cases

Niklas Widulle*, Luis Miguel Vieira da Silva*, René Heesch*, Julian Putzke*, Oliver Niggemann*
*Institut für Automatisierungstechnik
Helmut Schmidt Universität
Hamburg, Deutschland
{niklas.widulle, miguel.vieira, rene.heesch, julian.putzke, oliver.niggemann}@hsu-hh.de

***Abstract*—AI based planning methods are promising tools to allow CPS to achieve independent and optimal behaviour. Many research projects have developed a variety of planning algorithms with encouraging results. However, many of the developed algorithms are not yet capable to handle the complexity of real world problems. A roadblock in the development of more advanced solutions is the lack of real world benchmarks and applications. In this work we investigate how AI based planning methods can be applied to real world CPS use cases. These use cases are part of the research projects KIPRO, EKI and RIVA which are all part of the KIIPS research focus by dtec.bw. We show how these projects bring research into real world applications and help advance the state of the art of AI planning methods.**

***Index Terms*—cyber-physical systems, artificial intelligence, planning, machine learning**

I. Introduction

Cyber-physical systems (CPS) are characterized as highly complex, interconnected systems which combine physical and computational elements [1]. Examples of CPS are industrial manufacturing systems which are called cyber-physical production systems (CPPS), robotics systems or autonomous vehicles [2]. Depending on the type of CPS, the governing algorithms have different goals, including control, anomaly detection, diagnosis, (re-) configuration and especially planning, the process of making decisions towards a goal. Whether it is production sequence in a CPPS or a route generation for an autonomous vehicle, planning as a high level functionality plays a key role.

Recently, progress has been seen in the field of artificial intelligence (AI) based planning solutions. AI can be grouped into symbolic and subsymbolic methods. The former methods deal with discrete symbols and their relationships, while the latter focus on statistical relationships in data with the best known subgroup being machine learning (ML). Both groups provide methods that can be applied to planning as is shown in e.g.: [3], [4].

A big research community is working with the *planning domain definition* language (PDDL). It is a formal language that can be used to describe planning problems and falls in the symbolic category [5]. Another symbolic way to describe planning problems is within the formalisms of *boolean satisfiability problems* (SAT) and *satisfiability modulo theories* (SMT). SAT requires the planning problem to be described as a set of boolean statements and a SAT solver is then used to find a solution. SMT extends this to include background theories and is thus more expressive. ML is typically grouped in the three main directions supervised, unsupervised and reinforcement learning. Each of these three main categories has been applied to planning problems, with varying results.

The maturity of the approaches covered so far is very varied. Some have been applied only to very small toy problems, while for example PDDL has been used as a basis for scientific competitions. However, the application of these methods to real world problems is still limited. This is at least partially due to a chicken or the egg dilemma: Most approaches so far are not yet usable to cover real world problems but the scientific community lacks real world data to improve the approaches.

The solution can take the form of joint research projects that bring industry and scientific community together, as the research projects KIPRO [1], EKI [2] and RIVA [3] do. Each of these projects has its own scope on different aspects of research for CPS. In each one however, planning plays a significant role and therefore these projects are candidates for the application of AI planning approaches. Every project can provide additional insight into the application of these approaches and also provide much needed feedback and data for the research community.

In this work, the use of AI planning within the scope of these research projects is investigated. Potentials of the individual approaches within the use cases are highlighted and potential pitfalls and limitations are named. This lays the foundation for future work on AI planning within these projects.

The remainder of this paper is structured as follows: In the next section, a short overview of the state of the art in AI planning is given. Then the aforementioned research projects are introduced, highlighting use cases and potential benefits. This is followed by a more general discussion of these applications and resulting challenges. The conclusion and future work finish this paper.

[1]KIPRO – KI-basierte Assistenzsystemplattform für Produktionsprozesse
[2]EKI – Engineering für die KI-basierte Automation in Produktionsumgebungen
[3]RIVA – IT-Konzepte & -Lösungen für Verbünde autonomer Fahrzeuge

https://doi.org/10.24405/14547

II. State of the Art

In the following two subsections, an overview of AI planning methods is given. Requirements resulting from their use in CPS are also introduced.

A. Symbolic Planning Methods

Symbolic AI deals with high level symbols and their relationships. For planning, it can be used as follows: The planning problem needs to be described using these symbols and the solution can then be inferred from them. Thus, the solution process always consists of two steps: Describing the problem within the formalism of the chosen method and then applying a solver to derive the solution. The development of solvers is a large research topic on its own, but outside of the scope of this work. Here we focus on the modelling languages. Generating a formal description of a planning problem is not trivial in itself.

One common approach is the use of PDDL. The language helps to define a description format for planning problems. Depending on the version of the language, many common features of planning problems can be described, such as temporal constraints, numeric parameters or parallelism [6]. However, real world problems are often still too complex to be described within the stiff framework of the language [7]. Connected with PDDL, a number of solvers were developed, some solve the problem directly, while others translate the problem into another description such as SMT [8]. Solvers usually support only a subset of all features of a PDDL version, which makes the problem of the limited expressiveness of PDDL even worse [7].

The basis for using SAT for planning was laid by Kautz et al. in 1992 [9]. The basic method is to describe the problem within the formalism of SAT and then use a regular SAT solver to find the solution. Describing a planning problem in SAT is nontrivial however. Since SAT only supports boolean symbols, it is very limited. This can be overcome by employing SMT [3]. Using SMT for planning can be done by describing the problem directly as SMT or by using another problem description formalism and then translating it to SMT. SMT has its own widely used standardized language, specified as smt-lib. A notable extension for SMT is called OMT, which additionally includes methods for optimization [10]. This is obviously very beneficial for planning, since we are typically interested in an optimal solution.

B. Machine Learning based Planning Methods

Where symbolic methods typically fall short is in their inclusion of data. Modern CPS create vast amounts of data, and using them to create or improve plans can benefit the solution. This is where ML based methods can step in. The main drawback of these methods is that they require vast amounts of data that may not yet be available when the CPS is still in the design phase. Simulations can alleviate this problem. For an overview of ML based planning approaches refer to [11], only a brief impression is given here.

Supervised learning uses labeled data for training. Examples of recent applications of supervised learning for planning include STRIPS-HGN by Shen et al. [12] and GGS-NN by Li et al. [13]. The need for labeled data is a major drawback, since generating labels for data sets is usually labor-intensive and often impractical.

For this reason, unsupervised learning is promising, which does not require labels for training. Work in this direction is still in its infancy. An example is the work by Segovia-Aguas et al. [14], in which planning instances are classified using an unsupervised algorithm.

Recently, first benchmarks have been created for the use of AI and more specifically ML planning methods [15].

C. Requirements for the Application of Planning Algorithms

In a previous work, we derived requirements for the use of AI-based planning algorithms in CPPS, but they remain relevant to the more general case of CPS [16]. The requirements for the algorithms are:

- Optimization: The ability to provide an optimal solution
- Dependencies: Handling dependencies between tasks
- Loops: Managing recurrent actions
- Explainability: Be understandable by a human user
- Low Effort: Does not require too much human input
- Data: Makes use of existing data

For a more in-depth look at the reasoning for these requirements please refer to our previous work. In the description of our use cases and in the discussion we will refer back to these requirements.

III. Applications

In the following an introduction to the projects KIPRO, RIVA and EKI and the specific use cases within them is given.

A. KIPro

Modern production facilities still incorporate manual tasks. These manual production steps are frequent especially for assembly and in high variance or low volume production, which is common within the machine tool industry. Fully automating these production steps is typically unfeasible given the low volume, however, increases in efficiency are still required. This is especially true in high-wage countries such as Germany.

Worker assistance systems can alleviate the issue. They support the worker by providing information on the assembly task and therefore reduce idle time especially for inexperienced workers. Creating the assistance function with traditional methods still requires a lot of effort. Here, AI can step in: Using AI based planning algorithms creating assistance can be automated. Additionally it can be embedded into the automated planning and scheduling system of the factory to further increase productivity. This is the goal of the project KIPro: To create an AI enabled assistance system.

KIPro is a joint project by HOMAG[4], DUALIS[5], ITAC[6], TH OWL[7] and the Professorship Computer Science in Mechanical Engineering at HSU[8]. HOMAG is a leading manufacturer of woodworking machines. DUALIS is a solution provider for automatic planning and scheduling (APS) systems as well as other industrial software. ITAC creates manufacturing execution system (MES) software and related tools. Together with the input from the academic institutions these companies have the required know how and capabilities to create the assistance functionality envisioned in KIPro.

The assistance system needs to plan the assembly process in order to provide assistance to the worker. This makes the connection to AI planning methods clear. However, the input to the planning system can be CAD and video data from assembly sequences, and therefore not directly suitable for symbolic planning. The description of the planning problem is one of the areas of concern. There is a dedicated community to assembly sequence planning [17] which has created its own notations. A high level of automation for the generation of assembly plans is required in order to keep the solution economically viable. Therefore, in order to solve the issue we require an automatic creation of a problem description which can then be solved using a planner or we can alternatively rely on an integrated RL based approach. Both approaches are current research topics and solutions can benefit the wider community.

Additionally the assembly assistance functionality needs to be embedded in the APS and MES contexts. APS systems themselves can benefit from ML as the created schedules can be adapted automatically to changes in production context. The assistance functionality also needs to adjust to the worker, since they will require individual and adaptive levels of assistance. Here the integration into the MES context can be helpful as it provides information about the user.

B. EKI

The project EKI aims to develop an open, vendor independent and expandable engineering platform which enables the integration of AI components within the engineering process. In this case, engineering describes the process of creating or adapting the automation software of CPPS in order to manufacture new products or react to failures. The project tackles two challenges. On the one hand, AI applications such as predictive maintenance are getting more and more important and have to be integrated during the engineering process. Furthermore, due to the trend of CPPS, there are also new approaches to facilitate the engineering using AI-based assistance features for example, to automate the creation of sequences in PLCs. However, there is a lack of engineering methods enabling the usage of these new developments. On the other hand, due to the lack of the engineering methods, there are also only few CPPS. To solve this chicken or the egg dilemma, an AI-capable engineering platform is developed together with Weidmüller Interface GmbH & Co. KG and evaluated by engineering a CPPS for automotive glass finishing built by BBG GmbH & Co. KG.

Within the EKI project, AI planning methods will be used as the basis of the AI-based assistance feature to facilitate the engineering. For this purpose, it is assumed that within a modular CPPS, the functionality of a module is accessed as a so-called *skill*. The skills already programmed on the module's PLCs and can be called, for example via OPC UA, from a higher-level controller by specifying various required parameters [18]. Thus, the output of the assistance feature will be a sequence of parameterized skills, a high-level controller has to call in order to manufacture a desired product. An AI planning algorithm will take a description of the raw materials as the initial state and a description of the desired as the goal state. The possible actions, which can be performed to reach the goal state, are represented by the descriptions of the functionalities of the available modules, the so-called *capabilities* applied in [19].

In this project, we try to solve the planning problem from two different sides. On one hand, the symbolic approach, where we use logic solvers to resolve the planning problem. On the other hand, a subsymbolic method, which uses ML algorithms to generate the output sequence. The general input and output of both systems are the same, although the implementation is different. The two need a formal description of the domain, as well as the initial state of the process and the desired goal. The output is a sequence of actions leading from the initial to the goal state. On top of that, for each action, the individual parameters are defined in the planning tool. Consequently, the planning tool can output a combination of production sequence and parameters.

C. RIVA

The RIVA project aims to enable teams of robots of different modalities (land, water, air) to perform missions autonomously in real time. Autonomous robot teams have an enormous economic and societal potential, as many use cases can be realized more effectively and efficiently than with single robots. Such teams range from unimodal robot teams (e.g., drone swarms for fighting forest fires) to trimodal robot teams (e.g., search & rescue using boats, drones and rovers). An important part of the project is the planning and execution of missions based on the knowledge of the different capabilities of each robot, where changing environmental conditions or capabilities of the team participants can directly affect the tasks of the individual robot and must be taken into account. Various other challenges such as path planning, environment model creation or ensuring safe behaviour are addressed in this project. Mission accomplishment is to be demonstrated both in simulation and in practice. This problem is addressed in cooperation with IT-objects GmbH and Third Element Avi-

[4] HOMAG GmbH
[5] DUALIS GmbH IT Solution
[6] ITAC Software AG
[7] OWL University of Applied Sciences and Arts (TH OWL)
[8] HSU Helmut Schmidt University University of the Federal Armed Forces Hamburg

TABLE I: THE REQUIREMENTS OF AI PLANNING IN THE RESEARCH PROJECTS
●/◐/○: Important/Partly relevant/Less relevant

	Optimization	Dependencies	Loops	Explainability	Low Effort	Data
KIPro	●	●	○	◐	●	◐
EKI	●	●	●	●	◐	○
RIVA	◐	●	○	●	○	◐

ation GmbH, who provide the required hardware (multimodal robots) and the simulation environment.

In the RIVA project, AI planning methods will be used for mission planning. Teams of robots are used to implement complex scenarios. Due to this complexity, but also due to the diversity of the scenarios, the missions for the fulfillment of the scenarios are to be planned automatically. Accordingly, the wide range of possible applications for robot teams also requires a domain-independent approach to planning the desired missions. In contrast to the CPPS considered so far, a sequence of robot capabilities is output here instead of a sequence of production steps. The project is not about considering different approaches to solving the planning problem, but about creating the planning problem based on a formal model of autonomous robot capabilities to be developed in the project. The goal is to enable planning for all possible scenarios and robot types by basing the planning on the uniform description of the robots, which only needs to be transformed into the planning problem. Consequently, no individual planning problems have to be set up manually. Furthermore, three modalities are considered, which have hardly been applied so far. In addition to describing the robots and their capabilities, the initial situation of the robots and their environment as well as the mission objective must be considered. For example, the goal may be to transport an object from A to B, and the transport can be realized only by cooperation of multimodal robots due to obstacles. The output is also a sequence of actions or capabilities leading from the initial state to the goal state.

IV. DISCUSSION

Each of these projects use AI planning as a central part of their solution. The different projects applications, requirements and goals however still require distinct approaches.

A. Requirements for the Planning Approaches

Which methods are the best fit for each project is a difficult question. The requirements for planning algorithms established in our previous work can give a good indication [20]. For each of the projects, different requirements are more relevant. Since the planning methods only satisfy the requirements to varying degrees, this can give an indication which methods are best suited for the different use cases within the projects.

For KIPro, the assistance system needs to provide optimal solutions for the workers, otherwise the overall benefit is too low. Assembly processes are inherently interdependent. Loops and repetitive instructions are of less concern, while explainability is of some interest. The solution should overall remain economically viable and therefore low effort is essential. The usage of existing data is relevant to the improvement of APS results.

For an engineering tool like that created by EKI, explainable behaviour is highly important in order to be transparent to the user. Still, dependencies need to be resolved and an optimal solution should be provided. Loops will be part of the solution and need to be addressed accordingly. Currently, a lot of research is being done in the field of semantic descriptions of production facilities. It is hoped that in future, it is possible to use these descriptions to reduce the effort required to integrate the domain knowledge in planning algorithms. Thus, the effort is less important in this project.

In mission planning for autonomous and heterogeneous robots, as envisioned in RIVA, an optimal solution is not as necessary. Finding a solution for complex scenarios is challenging in itself. Dependencies between robots or between inputs and outputs of capabilities are on the other hand of importance, so that for example the battery life can be calculated. Loops are less of a concern for the RIVA project. Of high importance is explainability, since the behaviour of autonomous robots is already difficult to comprehend due to their highly automated capabilities. Therefore, planning should be explainable in order not to make the behavior of robots even more unpredictable. The effort required to create and maintain the solution is not as much of a focus. Neither is the use of the data in the focus. The data is of course important for the control of the internal state and consideration in the execution of their capabilities, but for the basic planning it should be considered and included in a rather limited way.

These notions are summarized in TABLE I. Together with the knowledge of the advantages and shortcomings of the different planning methods, some recommendations for the projects at hand can be derived.

B. Challenges and Potentials for Planning Approaches

For KIPro, using symbolic planning approaches, especially SMT to create optimal assembly plans is promising, especially since resolving dependencies becomes trivial. However, the form of the input models, be it CAD or video data, makes using just these methods impossible. What is required is an interconnected method which utilizes the power of ML to create input models suitable for symbolic AI methods. Alternatively, an end-to-end RL approach might resolve the task, here the computational effort could be the limiting factor. The additional inclusion of optimization for the APS results creates a scenario which resembles supervised learning because planning results can be matched with known outcomes.

Considering the strengths and weaknesses of the different AI planning methods, two approaches seem to be the most useful in the context of the EKI project. If the platform is used at the beginning of the operating phase of a CPPS, there is less or no labeled data available to train an ML-model. Thus, at this point in time, only a symbolic approach is feasible. As PDDL is not expressive enough to describe and consider the complex dependencies between the input and output products as well as the parameters, it has to be an SMT-based approach. But, in the course of the operating phase of a CPPS, it is possible to collect the data about the different products as well as the corresponding sequences of actions leading to the products. Therefore, also an ML-based approach may be an interesting option at a later point in the operating phase. As the collected data will be labeled, a supervised learning algorithm might be promising. However, using ML-based methods brings new challenges, as learning extensive ML-models cannot be done on a PLC. This makes the integration of cloud computing or edge devices with sufficient computing power necessary. There is also the question whether inference must be real-time capable and run on the PLC, and how this can be ensured. These challenges will also be addressed within the EKI project.

In the RIVA project, the use of symbolic planning approaches for mission generation is promising. On the one hand, formal capability models have a close proximity to these planning approaches, on the other hand, the advantageous properties of sub-symbolic planning approaches are hardly relevant here and take place in the use of a robot's autonomous capabilities, such as in environment perception. Especially PDDL is in strong focus for planning in the field of autonomous robots. Therefore, the focus is on symbolic planning approaches in conjunction with formal capability models for the robots.

In each of these projects, a combination of symbolic and subsymbolic methods is most promising. While the reasons for this are diverse, it highlights the necessity for research into combining these domains for planning approaches.

V. Conclusion and Future Work

The three research projects KIPro, RIVA and EKI each show the potential for successful applications of AI based planning. While their applications - autonomous vehicles, engineering tools and assembly systems - are very different, each project offers the opportunity to apply these methods. In the future, this will hopefully allow us to overcome one of the main limitations in the development of AI based planning methods, which is the lack of real world benchmarks and data.

The analysis of existing planning approaches for the projects showed that combining symbolic and subsymbolic methods holds the greatest potential. This is an exciting and promising field for future research in the planning domain.

Acknowledgment

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project KIPRO][project RIVA][project EKI].

References

[1] R. Baheti and H. Gill, "Cyber-physical systems," *The impact of control technology*, vol. 12, no. 1, pp. 161–166, 2011.

[2] J. Shi, J. Wan, H. Yan, and H. Suo, "A survey of cyber-physical systems," in *2011 international conference on wireless communications and signal processing (WCSP)*. IEEE, 2011, pp. 1–6.

[3] A. Bit-Monnot, F. Leofante, L. Pulina, and A. Tacchella, "Smt-based planning for robots in smart factories," in *International Conference on Industrial, Engineering and Other Applications of Applied Intelligent Systems*. Springer, 2019, pp. 674–686.

[4] J. P. Usuga Cadavid, S. Lamouri, B. Grabot, R. Pellerin, and A. Fortin, "Machine learning applied in production planning and control: a state-of-the-art in the era of industry 4.0," *Journal of Intelligent Manufacturing*, vol. 31, no. 6, pp. 1531–1558, 2020.

[5] C. Aeronautiques, A. Howe, C. Knoblock, I. D. McDermott, A. Ram, M. Veloso, D. Weld, D. W. SRI, A. Barrett, D. Christianson *et al.*, "PDDL— The Planning Domain Definition Language," Technical report, Tech. Rep., 1998.

[6] A. Anis, W. Schäfer, and O. Niggemann, "A comparison of modeling approaches for planning in cyber physical production systems," in *Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA)*. IEEE, 2014, pp. 1–8.

[7] A. Rogalla, A. Fay, and O. Niggemann, "Improved Domain Modeling for Realistic Automated Planning and Scheduling in Discrete Manufacturing," in *2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA)*, vol. 1, 2018, pp. 464–471.

[8] M. Cashmore, M. Fox, D. Long, and D. Magazzeni, "A compilation of the full pddl+ language into smt," in *Proceedings of the Twenty-Sixth International Conference on International Conference on Automated Planning and Scheduling*, ser. ICAPS'16. AAAI Press, 2016, p. 79–87.

[9] H. Kautz and B. Selman, "Planning as Satisfiability," in *Proceedings of the 10th European Conference on Artificial Intelligence (ECAI 92)*, 1992.

[10] F. Leofante, E. Giunchiglia, E. Ábrahám, and A. Tacchella, "Optimal planning modulo theories," in *Proceedings of the Twenty-Ninth International Joint Conference on Artificial Intelligence, IJCAI 2020*, C. Bessiere, Ed. ijcai.org, 2020, pp. 4128–4134.

[11] S. Jiménez, T. de La Rosa, S. Fernández, F. Fernández, and D. Borrajo, "A review of machine learning for automated planning," *The Knowledge Engineering Review*, vol. 27, no. 4, pp. 433–467, 2012.

[12] W. Shen, F. Trevizan, and S. Thiébaux, "Learning domain-independent planning heuristics with hypergraph networks," in *Proceedings of the International Conference on Automated Planning and Scheduling*, vol. 30, 2020, pp. 574–584.

[13] Y. Li, D. Tarlow, M. Brockschmidt, and R. Zemel, "Gated graph sequence neural networks." [Online]. Available: http://arxiv.org/pdf/1511.05493v4

[14] Javier Segovia-Aguas, Sergio Jiménez, and Anders Jonsson, "Unsupervised classification of planning instances," *Proceedings of the International Conference on Automated Planning and Scheduling*, vol. 27, pp. 452–460, 2017.

[15] J. Ehrhardt, M. Ramonat, R. Heesch, K. Balzereit, A. Diedrich, and O. Niggemann, "An ai benchmark for diagnosis, reconfiguration planning," in *2022 27th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA2022)*, 2022.

[16] A. Köcher, R. Heesch, N. Widulle, A. Nordhausen, J. Putzke, A. Windmann, and O. Niggemann, "A research agenda for ai planning in the field of flexible production systems," in *2022 IEEE 5th International Conference on Industrial Cyber-Physical Systems (ICPS)*. IEEE, 2022, pp. 1–8.

[17] B. Deepak, G. Bala Murali, M. R. Bahubalendruni, and B. Biswal, "Assembly sequence planning using soft computing methods: a review," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 233, no. 3, pp. 653–683, 2019.

[18] A. Köcher, T. Jeleniewski, and A. Fay, “A Method to Automatically Generate Semantic Skill Models from PLC Code,” in *IECON 2021 - 47th Annual Conference of the IEEE Industrial Electronics Society*. Piscataway, NJ: IEEE, 2021, pp. 1–6.

[19] A. Köcher, C. Hildebrandt, L. M. Vieira da Silva, and A. Fay, “A Formal Capability and Skill Model for Use in Plug and Produce Scenarios,” in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, vol. 1, 2020, pp. 1663–1670, ISSN: 1946-0759.

[20] R. Heesch, N. Widulle, A. Köcher, A. Nordhausen, L. M. Vieira da Silva, J. Putzke, and O. Niggemann, *Methoden der künstlichen Intelligenz für die automatisierte Planung von modularen Produktionsprozessen*, ser. Automation 2022: Automation creates Sustainability. Düsseldorf: VDI Verlag, 24.08.2022 2022, pp. 439–452. [Online]. Available: https://doi.org/10.51202/9783181023990-439

Avoiding Electromagnetic Interference Induced Risks for Autonomous Driving

Unai Aizpurua, Tim Brandt, Michael Hagel,
Erik Kampert, Marita Wendt,
Stefan Dickmann, Klaus Hoffmann, Marcus Stiemer
Faculty of Electrical Engineering
Helmut Schmidt University
22043 Hamburg, Germany
stefan.dickmann@hsu-hh.de

Roland Eidher, Hermann Aichele
Robert Bosch GmbH
Stuttgart, Germany

***Abstract*—Autonomous vehicles require an extremely high safety level, whereas their functionality is based on a high density of electronic components and sensing systems. As a consequence, electromagnetic compatibility does not only become even more challenging than usual in electronics development, but the influence of unintended and intended electromagnetic interferences must also be assessed under future autonomous driving level 3 to 5 scenarios, which differ significantly from today's ones. In this work, an overview is provided of the possible interference sources that need to be taken into account. Currently used electromagnetic immunity tests are described for two specific automotive components. It is explained where these methods require improving to adapt to the enhanced requirements of automated driving and how this future-proofing can be achieved.**

***Index Terms*—electromagnetic compatibility, autonomous driving, electromagnetic interference, power electronics, artificial intelligence**

I. Introduction

Autonomous driving (AD) and vehicle electrification determine the future frame conditions for competition in the automotive industry. Both technical trends require fundamental progress on guaranteeing electromagnetic compatibility (EMC) at both component and vehicle level [1]. In particular, immunity is needed against electromagnetic interference (EMI) caused by the vehicle itself, as well as against external interferences, including intended electromagnetic interference (IEMI) as part of criminal activities.

With increasing automated driving level of a vehicle [2], the number of implemented safety and comfort related driving functions and the number of vehicular system states increase rapidly, which in turn strongly impacts the complexity and effort of EMC testing. At the simplest level, a sensor affected by (I)EMI could provide wrong, delayed or no data at all to an electronic control unit (ECU) that depends on its feedback, thereby affecting its decision making process, possibly leading to unintended actions or dangerous manoeuvres [3].

At the level of the vehicle, the vast number of EMC test iterations required to guarantee safe and reliable automated driving thus asks for a different approach. It is expected that a combination of standard established EMC tests with virtual tests, based on validated numerical models and simulations, could provide a great win in time and effort. Furthermore, such EMC test results can then be used for the training of artificial intelligence (AI) methods with the aim to extract hidden dependencies between system parameters and the resulting EMC behaviour. This enables predictions of the impact on EMC of planned technical alterations during a product's development phase.

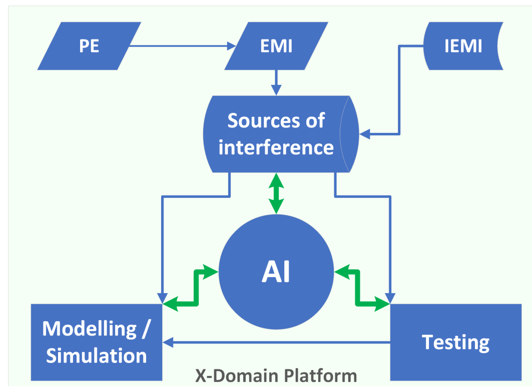


Figure 1: Process overview for the improvement of automotive electromagnetic immunity, incorporating modern power electronics as a source of EMI, and the AI-supported evaluation of the synergies between modelling, numerical simulations and physical tests.

Vehicle electrification enables a manifold of applications, including those that require high electrical power. Modern electrical systems can be distributed all over the vehicle due to their relatively small form factor and the abundance of power supply lines throughout the vehicle. Several of these systems temporarily require high currents as part of their standard operation, during which their supply lines can generate magnetic field disturbances in nearby systems. These magnetic fields can either induce currents in nearby cabling or directly affect systems that include passive, permanent magnetic elements, such as the magnetoresistive sensors used in automotive tra-

This paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr, which we gratefully acknowledge [project ESAS – Elektromagnetische Störfestigkeit autonomer Systeme].

https://doi.org/10.24405/14548

jectory, angle, current and magnetic field measurements [4]. An additional EMC challenge that originates from increased vehicle electrification is conducted EMI caused by switching transients of the various power converters used throughout the modern vehicle.

The aim of the research reported in this paper is to achieve a multi-factorial engineering approach adapted to current automotive developments in order to improve and facilitate the electromagnetic immunity of automotive components and (sub-)systems. This includes the study of modern interference sources, e.g., due to power electronics (PE) or malicious attacks. First, a systematic evaluation of the test requirements for current and future AD components and systems is to be carried out. Based on these results, potential gaps in existing EMC standards and methods must be identified and closed, e.g. extended by new or adapted virtual tests and subsequently combined into an AI-based analysis methodology, as schematically represented in FIGURE 1.

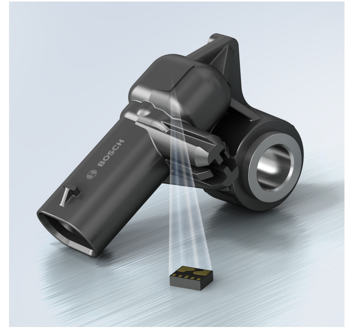
II. BACKGROUND

A. Devices under test

Two exemplary automotive components used in current automated driving and evolving into AD systems are an acceleration sensor shown in FIGURE 2a and an electric power steering unit in FIGURE 2b. The former is mainly designed for impact detection, whereas the latter controls and assists the vehicle steering.

The two-channel peripheral accelerometer that will be used as a device-under-test (DUT) in this study provides information on direction and level of impact by measuring accelerations along two spatial axes. Such accelerometers are installed at more than twenty locations in a typical vehicle, e.g., mounted at the various sides and crumple zones of the vehicle to improve impact detection and airbag deployment as well as near the wheels for active suspension to enhance driving comfort. The accelerometer contains a micromechanical sensor element comprising fixed and moving finger structures and spring pins. The seismic mass with its comb-like electrodes is resiliently suspended in the metering cell. A linear acceleration in the sensing direction changes the distance between the moving and fixed structures, which alters the overall capacitance [5]. The associated measured electronic signal is then amplified, filtered and digitized by an application-specific integrated circuit and transmitted to an ECU over a single pair of insulated copper wires.

The second DUT in this study is a modular built electric power steering unit that supports advanced driver assistance functions (ADAS), in which an electric servomotor converts a torque via a worm gear and transfers it to the steering rack by a pinion. Such unit has among the strictest requirements for electromagnetic compatibility and immunity. In the electric power steering system, a torque sensor on the steering pinion measures the torque that the driver applies to the steering wheel. Based on these data, the electronic control unit calculates the steering assistance, which the electric motor needs to apply. A magnetic pole wheel is fitted on the input shaft that is connected to the steering pinion by means of a torsion bar. When a driver applies torque to the steering wheel, the torsion bar is rotated and, in turn, the magnets' relative positions to the sensor are altered, changing its magnetoresistance [6].



(a) Accelerometer

(b) Electric power steering unit

FIGURE 2: DEVICES UNDER TEST USED AS EXEMPLARY AD COMPONENTS IN THE EMC STUDY. © ROBERT BOSCH GMBH

B. EMC requirements by manufacturers

International EMC standards exist for most electronic, electric and electromechanical equipment, in particular for consumer products, such as for road vehicles and their corresponding (sub-)systems and components [7]. Automotive original equipment manufacturers (OEMs) impose additional test requirements on their Tier-1 suppliers based on their market and customer-specific needs. These typically extend the frequency range and the amplitude of the interference signals for those tests, decrease the frequency step width, and eventually add specific signal modulations, thus increasing the test effort in both cost and time.

As part of the work presented here to understand the impact of EMC test requirements for current and future AD components on existing EMC standards and methods, such additional OEM requirements were analyzed for approx. 50 automotive OEMs for three common EMC test methodologies, namely bulk current injection (BCI), radiated immunity portable transmitter (RIP), and radiated immunity (RI). In this paper the focus of the requirement analysis is on BCI, as a crucial test methodology to investigate the effects of EMI induced by novel PE components introduced for vehicle electrification [8].

FIGURE 3 provides an overview of the OEM-specific requirements for BCI current levels at selected frequencies for both open and closed loop tests, represented by a boxplot that is confined by the 25th and 75th percentiles. Moreover, all outliers are displayed as individual symbols, further highlighting the large spread in individual OEM requirements. In comparison, the BCI currents for the lowest test severity level, provided in the standard from the safety electronics working group of the German Association of the Automotive Industry, are shown as a dashed line [9]. As these are minimum requirements, these levels mostly correspond with the lower ends of the boxes in FIGURE 3.

Parts of the observed spread and the higher BCI current levels in the OEM requirements are thus due to increased electromagnetic immunity targets depending on the safety criticality of the same OEM's component class, typically increasing 6 dB with function reliability needs. Nevertheless, for various test frequencies, i.e. 1, 30 and 400 MHz, the displayed spread is multiple orders of magnitude larger, up to 73 dB. Subsequently, this requires signal generation and measurement equipment with extensive dynamic ranges, possibly demanding additional power amplifiers. More specifically for BCI-based EMC measurements, the injection and monitoring probes are limited in power and frequency range, thus potentially requiring a physical exchange during an EMC test sequence, adding further to the test's duration, effort and cost.

Therefore, for EMC testing in general, an intelligent, reduced selection of the most relevant EMC parameters is expected to provide large benefits, which can then be further adapted to the manufacturer's or customer's need. As envisioned in the research presented here, such selection could be based on the AI-supported analysis of physical tests combined with numerical simulation results that are based on established DUT-models. This is expected to enable the prediction of crucial measurement ranges for certain adaptations of a known EMC-compliant DUT or of its installation environment.

C. Complementary electromagnetic immunity test methods

Various electromagnetic immunity test methods have been developed during the last decades and are currently employed to verify the EMI immunity of DUTs. As mentioned before, those measurement approaches are defined in common international EMC standards, with generic or specific scopes, for example those developed for the automotive industry. The principal immunity test methods involve either an absorber-lined shielded enclosure (ALSE) also known as a semi-anechoic chamber (SAC), an open-area test site (OATS), a BCI, a stripline, a gigahertz transverse electromagnetic (GTEM) cell or an electromagnetic reverberation chamber (RC), each with its advantages and disadvantages. The ALSE method is by far the most widespread within the EMC community, as the required SAC is also used for other common EMC tests, in particular for those involving radiated emissions. Hence, extensive literature exists for immunity tests of automotive equipment employing the ALSE methodology, as well as for comparisons of various immunity test setups [10]–[13].

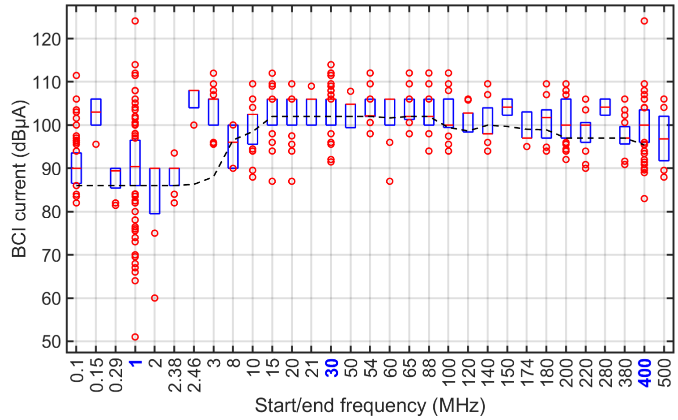


FIGURE 3: BOXPLOT OVERVIEW OF THE VARIATION IN BCI CURRENT REQUIREMENTS BY OEMS FOR VARIOUS SPECIFIED START AND END FREQUENCIES. ON EACH BOX, THE HORIZONTAL RED MARK INDICATES THE MEDIAN, AND THE BOTTOM AND TOP EDGES OF THE BOX INDICATE THE 25TH AND 75TH PERCENTILES, RESPECTIVELY. OUTLIERS ARE PLOTTED AS INDIVIDUAL SYMBOLS. THE DASHED LINE REPRESENTS BCI TEST PARAMETERS FOR THE AK-LV27-VALIDATION OF LEVEL-1 DUTS [9].

Investment in an ALSE is cost-inefficient if it is intended to only be used for immunity tests of automotive components [13]. On the other hand, both BCI and stripline methods are limited in their usable frequency range [14], [15]. The main disadvantage of GTEM cells is their volume limitation and its impact on maximum DUT size [16]. As for the OATS, the main disadvantages are quite obvious [17]: the dependency on weather conditions, the possible RF interference from the external environment and the possible public exposure of confidential test sequences. Recently, the RC is gaining appreciation as an electromagnetic immunity test approach, because it lacks some of the above mentioned disadvantages. As a consequence, corresponding immunity test standards, e.g., ISO 11452-11, have been published more than 15 years after those for other methodologies. The RC's advantages comprise a full shielding with respect to the environment, the reduction of the RF power required for an equivalent E-field strength, the large frequency interval supported that is only bounded from below by the RC's lowest usable frequency (LUF), which depends on the RC's dimensions (for RC dimensions of about 1x1x1 m, a LUF of approx. 1 GHz is obtained), and the reduction in measurement time as inside an RC the DUT is simultaneously illuminated from all sides and with multiple E-field polarities [18], which might also result in a reduction of uncertainty. However, in an RC it is impossible to study an entirely defined irradiation situation and results need to be validated on a statistical base.

III. EMI CAUSED BY ON-BOARD POWER ELECTRONICS

PE systems are used in electric vehicles (EV) in applications such as drive inverters, on-board chargers and DC/DC converters and are subject to strict specifications [19]. Their weight and volume are largely determined by passive components such as transformers, inductors, filters, capacitors

TABLE I: PHYSICAL CHARACTERISTICS OF SI, 4H-SIC AND GAN SEMICONDUCTORS. ADAPTED FROM [20].

Parameter	Unit	GaN	4H-SiC	Si
Bandgap, E_g	eV	3.45	3.26	1.12
Electrical breakdown field, E_c	kV/cm	2000	2200	300
Electrical mobility, μ_n	cm^2/V·s	1250	1000	1500
Hole mobility, μ_h	cm^2/V·s	850	115	600
Saturated electron drift velocity, v_{sat}	$\cdot 10^7$cm/s	2.2	2	1
Thermal conductivity, λ	W/cm·K	1.3	4.9	1.5

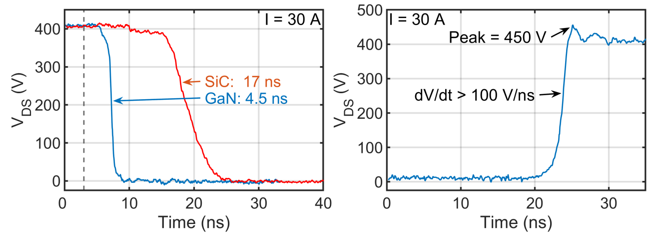
and heat sinks for the semiconductors. The use of smaller passive components is possible by increasing the switching frequency, but this also increases the losses in the switching components. The latter problem can be mitigated by using wide-bandgap (WBG) power semiconductors, such as SiC or GaN instead of Si devices. These WBG semiconductors have various advantageous physical properties compared to their silicon counterparts, which are summarised in TABLE 1 [20]. The electrical properties of SiC and GaN result in a lower on-resistance and thus in lower conduction losses, which enable higher switching rates, with GaN devices being up to four times faster than SiC-based switches, as shown in FIGURE 4a.

As part of the research presented here, the interference potential of PE components within an EV's electrical system is investigated. The effects can generally be categorised into three groups:

a Annoying effects, e.g., disturbance in radio transmission or display function, strobing LED's, etc.
b Disturbing effects, e.g., sudden reset or disturbance of on-board digital equipment, changes in input/output (I/O) data status, etc.
c Catastrophic effects, e.g., loss of control of operational sections or data, failure of electronic components, change of threshold settings, catastrophic failure/accident, etc.

In a typical EV, several systems utilise PE circuits: one or more traction converters, an on-board charger as a controlled rectifier, and various isolating or non-isolating DC/DC converters for the on-board power supply with different voltages. For the drive or traction inverters of such EVs, the switching frequencies are mostly of moderate magnitude. Furthermore, because of the parasitic capacitances of the stator windings and because of the risk of partial discharge, high rise times ($\frac{\partial u}{\partial t}$ values) should be avoided from an EMC point of view. The recommendation for standard stators is 5 V/ns, which is orders of magnitude below the range that can be achieved with WBG power semiconductors (>100 V/ns), as shown in FIGURE 4b. Combined with the fact that mitigating measures are achieved with little to moderate effort, EMI emitted by drive converters and the effects on AD are not the main focus of the research presented here. Furthermore, as on-board chargers are not in charging mode whilst driving, they are also regarded as less relevant to this study.

Isolating DC/DC converters use a transformer to achieve galvanic isolation, which on the one hand has a beneficial



(a) Fall time GaN vs. SiC (b) Rise time GaN-FET

FIGURE 4: HARD SWITCHING PERFORMANCE OF WBG POWER DEVICES, WITH A) THE COMPARISON OF FALL TIMES OF GAN VERSUS SIC DEVICES, WITH THE FORMER BEING FOUR TIMES FASTER, AND B) THE STEEP RISE TIME OF A GAN-FET. ADAPTED FROM [21].

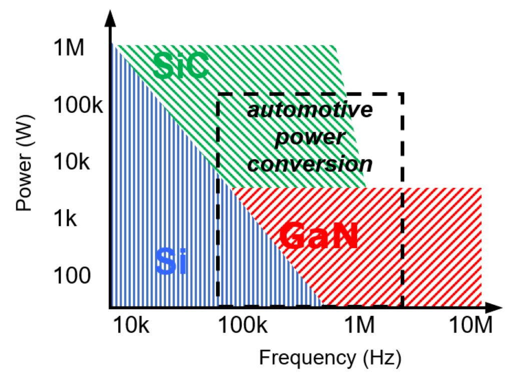


FIGURE 5: PERFORMANCE OF GAN, SIC AND SI-SEMICONDUCTORS USED IN AUTOMOTIVE PE DEVICES.

effect on the transients (inductive base load for low load commutation), on the other hand, however, might produce EMI with the transformer acting as an antenna. A *worst case*-scenario is examined in this study, namely investigating what challenges arise with extremely steep rise times. Non-isolating DC/DC converters with fast-switching semiconductors and therefore extremely fast-switching times as a source of interference are particularly well suited for this, with those using WBG semiconductors generating very steep transients in hard switching mode.

SiC and GaN devices have the potential to enhance the performance of PE in EVs, as they are able to operate at higher switching frequencies with overall lower losses than those of traditional silicon devices, as shown in FIGURE 5. Autonomous EVs can benefit from the use of SiC or GaN FETs in on-board PE systems, as using high switching frequencies has a positive effect on the efficiency and power density of the systems. Additionally, unlike Si- and SiC-based devices, GaN transistors do not have a body diode in their structure, so they lack blocking delay losses.

WBG power semiconductor devices, their potential and their rational use for efficient electric energy transformations have been well investigated [22], and the advantages of GaN semiconductors over SiC- and Si-based devices for the switching in different DC/DC converters in EV applications has been evaluated by comparing their total switching losses [23]. Based on the above investigations, two types of WBG devices are developed in different DC/DC converters of two I/O voltage ranges with switching frequencies up to approx. 1 MHz, which requires the observation of best layout practises and PCB design guidelines [24]. The two converters under consideration are:

1) from 200–480 V to 48 V based on SiC and/or GaN devices
2) from 48 V to 12 V based on GaN devices

It is expected that 48 V converters will become increasingly predominant in future vehicles, and that GaN technology will become attractive for the conversion of 48 V to 12 V and vice versa. Hence, it is necessary to take the associated additional EMC challenges into account, with the very high transients of up to 100 V/ns posing a particular challenge. These transient's slopes and additional resonances due to parasitic inductances and capacitances in the device can produce considerable conducted and radiated EMI at frequencies up to the low gigahertz range, depending on the specified accepted levels and safety margins.

WBG-devices as EMI noise sources have been investigated before [25], [26], however, the important question of the magnitude and influence of electromagnetic emissions stemming from WBG-semiconductors in autonomous EVs seems not to be adequately considered in the literature so far, although the EMC properties of DC/DC converters used in EVs, which could influence sensors and other devices vital for the overall reliability of the system, are of utmost importance.

As a next step, new EMI/EMC challenges emanating from the use of WBG technology in EV DC/DC converters will be examined and quantified. Utilising WBG circuitry, EMI/EMC will be considered as well, investigating possibilities to avoid potential interference at the source or to minimize its propagation within the vehicular system, primarily focusing on conducted emissions. Nevertheless, with increasing PE device switching frequency and rise time, the risk of radiated EMI increases rapidly, hence the shielding of assemblies, cables and connectors will require additional attention.

IV. IEMI by AD-relevant high power electromagnetics

IEMI threat scenarios have been characterized in the literature in terms of the classes in which their sources can be divided; their impact, performance and efficiency; and their likelihood to occur in the typical environment of a DUT or system under test [27]. It was concluded that criminal attacks executed by small groups or individuals are expected to be limited to constructions for electromagnetic wave emulation that are low-cost; small-sized; highly mobile; require little expertise in design and operation; and have a high component availability. Hence, their main modules typically constitute a high-power impulse source, an RF-modulator and a matching antenna. For the generation of effective ultra-wideband (UWB) pulses this involves a large capacitor, a spark-gap and an antenna that also serves as resonator, as shown in Figure 6.

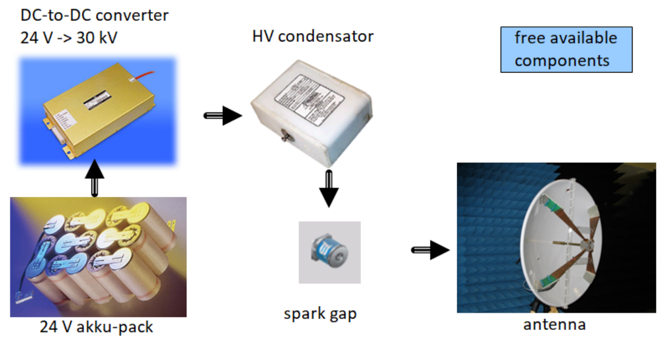


Figure 6: Typical components for the assembly of a simple UWB-based IEMI source. © WIS[1]

The high power electromagnetic (HPEM) capabilities at the Bundeswehr Research Institute for Protective Technologies and CBRN Protection (WIS[1]) in Munster are specifically tasked to investigate the disruptive effect of HPEM attacks. A variety of indoor and outdoor facilities exists for the simulation of attacks with (non-)nuclear electric pulses, which are of particular interest for investigating the effects of attacks on autonomous vehicles. Among others, a high-power microwave-generator for the frequency range of 0.675–3 GHz and a maximum power of 500 MW (Figure 7a and Figure 7b), a GTEM-chamber for the frequency range of 0–18 GHz operated at 50 kV, UWB pulse generators, wideband antenna systems and open waveguides are employed.

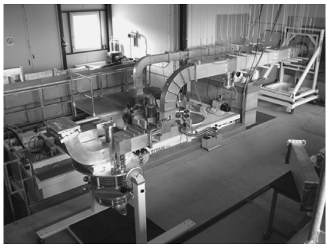
As mentioned above, UWB pulse-generators in combination with dedicated antenna systems are of particular interest. The pulse generators at WIS allow adjusting the pulse rise time and pulse duration. To avoid damage to the DUT, the intensity is adjusted by placing a damper between the pulse-generator and the antenna or by increasing the distance between the antenna and the DUT. As a very direct and powerful test method, a *Diehl suitcase* (Figure 7c) is available at WIS, deliberately constructed to reproduce plausible IEMI-attacks. The corresponding waveform for a typical HPEM-pulse at 1 m distance from a Diehl DS-110 generator is displayed in Figure 7d [28].

V. AI-based EMC development and analysis

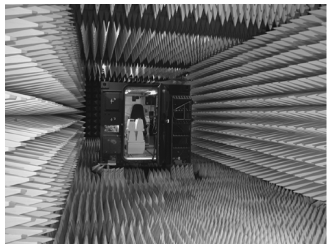
Currently, the capacity of methods from AI are tested in many research and application fields to control industrial processes, including the design of new industrial components, e.g., for applications to enhance electronic design automation [29]–[32]. This includes the study of the potential of AI methods to improve the EMC properties of autonomous devices and their resilience to (I)EMI.

The term *artificial intelligence* has various definitions and a diffuse extension. Within this work, the focus is on machine learning (ML) processes. In an engineering context, ML is usually considered as the behaviour of agents which obtain

[1]WIS is a departmental research institute of the German Federal government and is subordinate to the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support (BAAINBw).

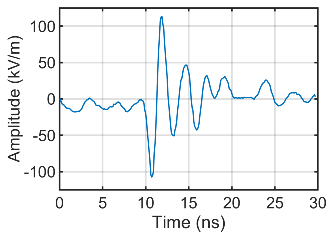


(a) HPM facility



(b) Ferromagnetic chamber inside AC

(c) *Diehl suitcase* with external power supply



(d) DS-110 waveform at 1 m distance. Adapted from [28].

FIGURE 7: HPEM CAPABILITIES FOR IEMI TESTS AT WIS. © WIS[1]

feedback from their environment (via sensors) and optimize their output (e.g., the action of particular actors) according to a calculable score or metric. These ML methods include the identification of parametric models, such as support vector machines, deep neural networks and, particularly, more sophisticated methods such as convolutional neural networks, transfer learning or reinforcement learning [33].

In contrast to many fields of data analytics, data usually do not arise abundantly in an engineering context and particular methods for their allocation have to be developed. To learn from the performance of previous designs, measurements of their performance can be used for the assignment of labels to parametric representations of EMC-relevant design parameters. This enables a supervised learning process as usually employed in regression processes, to create models that allow for the prediction of new designs or for classification of suitable and improper designs. If insufficient data are available, simulations can replace legacy data to provide labels for design proposals. However, such simulations have to be designed to capture the behaviour of the system sufficiently accurate and they must be inexpensive as well. To this end, multi-physical simulation is part of the overarching *cross-domain* (X-domain) platform indicated in FIGURE 1. In a mature state, the simulation can qualify to be part of a *digital twin* of an AD vehicle representing its EMC-relevant parts. In connection to such digital twin, the role of AI is not restricted to parameter identification, but can also become a part of the digital twin to model functions that are difficult to capture by physical modelling.

Classical ML procedures drive the identification of a model's internal parameters by minimizing the discrepancy of the model output to labels provided to the learning data, which are either measured in a suitable metric (supervised learning) as used for regression or classification problems, or by clustering the data according to certain rules (unsupervised learning). On the other hand, reinforcement learning resorts to a score that is assigned to the perceived environment and needs no direct labeling of its output. Then a *policy prediction* of how to interact with the environment is permanently adapted to maximize this score based on a Bellman equation [33]. To predict the impact of changes of the environment on this score, usually deep neural networks are employed, which are often more adequate for industrial as well as design processes, and hence part of the research presented here. In particular, this avoids the expensive process of labeling and reduces the amount of required data.

VI. CONCLUSIONS

This paper presents the proposed steps to enhance electromagnetic immunity of autonomous and electrified vehicles. It is explained that vehicular acceleration sensors and the electrical power steering sub-system are of particular interest as automotive DUTs, and that modern EMC test methods such as the RC can be used as a faster test practice, which involves the investigation of well-defined, simultaneous irradiation of DUTs with multiple E-field polarities on a statistical base. Power electronic components are shown to become much more prevalent in future EVs, hence their impact as EMI sources needs to be studied with particular attention. To this extent, new wide-bandgap semiconductor-based devices with increased switching rates are being introduced in DC/DC-converters in order to determine the effects of their transients on automotive DUTs. Further interference studies on these DUTs involve HPEM IEMI signals caused by plausible criminal techniques.

The synergies between modelling, numerical simulations and physical tests will be evaluated by means of an AI-methodology based on ML processes. This supports the aim of this research to achieve a multi-factorial engineering approach adapted to current automotive developments that improves the electromagnetic immunity of automotive components and (sub-)systems.

ACKNOWLEDGMENT

This paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr, which we gratefully acknowledge [project ESAS – Elektromagnetische Störfestigkeit autonomer Systeme].

REFERENCES

[1] A. R. Ruddle and A. J. M. Martin, "Adapting automotive EMC to meet the needs of the 21st century," *IEEE Electromagnetic Compatibility Magazine*, vol. 8, no. 3, pp. 75–85, 2019.

[2] SAE International, "Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles," SAE J3016, 2021.

[3] D. Hamann, O. Döring, and S. Koj, *EMV in der Kfz-Technik*, ser. GMM-Fachberichte. Society of Microelectronics, Microsystems and Precision Engineering (VDE/VDI GMM), 2022, ch. 12 - Elektromagnetische Resilienz autonomer Fahrfunktionen, pp. 72–76.

[4] L. Jogschies, D. Klaas, R. Kruppe, J. Rittinger, P. Taptimthong, A. Wienecke, L. Rissing, and M. C. Wurz, "Recent developments of magnetoresistive sensors for industrial applications," *Sensors (Basel, Switzerland)*, vol. 15, no. 11, pp. 28 665–28 689, 2015.

[5] Robert Bosch GmbH, *Bosch Automotive Electrics and Automotive Electronics: Systems and Components, Networking and Hybrid Drive*. Wiesbaden: Springer Fachmedien Wiesbaden, 2014, ch. 11 - Sensor types, pp. 310–353.

[6] Robert Bosch GmbH, *Bosch Automotive Electrics and Automotive Electronics: Systems and Components, Networking and Hybrid Drive*. Wiesbaden: Springer Fachmedien Wiesbaden, 2014, ch. 10 - Sensor measuring principles, pp. 232–309.

[7] ISO 11452-1, "Road vehicles — Component test methods for electrical disturbances from narrowband radiated electromagnetic energy — Part 1: General principles and terminology," International Organization for Standardization, Standard, 2015.

[8] ISO 11452-4, "Road vehicles — Component test methods for electrical disturbances from narrowband radiated electromagnetic energy — Part 4: Harness excitation methods," International Organization for Standardization, Standard, 2020.

[9] AK-LV 27 / AK-LV 29, "Part 3 - EMC requirements," German Association of the Automotive Industry (VDA), Standard V2.06, 2010.

[10] E. Borgstrom, "A comparison of methods and results using the semi-anechoic and reverberation chamber radiated RF susceptibility test procedures in RTCA/DO-160D, change one," in *2002 IEEE International Symposium on Electromagnetic Compatibility*, vol. 1, 2002, pp. 184–188 vol.1.

[11] R. De Leo and V. Primiani, "Radiated immunity tests: Reverberation chamber vs. anechoic chamber results," in *2005 IEEE Instrumentation and Measurement Technology Conference Proceedings*, vol. 1, 2005, pp. 337–341.

[12] C. Fanning, "Achieving correlation of radiated RF immunity testing performed in an absorber lined shielded enclosure and a mode tuned reverberation chamber," in *2006 IEEE International Symposium on Electromagnetic Compatibility, 2006. EMC 2006.*, vol. 3, 2006, pp. 817–822.

[13] N. Aggarwal, M. Al-Hamid, R. Vick, and S. Schulze, "GTEM cell – an alternative immunity test environment for automotive components," in *2021 IEEE International Joint EMC/SI/PI and EMC Europe Symposium*, 2021, pp. 469–474.

[14] P. S. Crovetti and F. Fiori, "A critical assessment of the closed-loop bulk current injection immunity test performed in compliance with ISO 11452-4," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 4, pp. 1291–1297, 2011.

[15] P.-A. Buta, C. Pirvu, C. Balan, R. Aipu, and A. De Sabata, "Stripline measurements in automotive EMC: A case study," in *2018 International Symposium on Electronics and Telecommunications (ISETC)*, 2018, pp. 1–4.

[16] T.-H. Loh and M. J. Alexander, "A method to minimize emission measurement uncertainty of electrically large EUTs in GTEM cells and FARs above 1 GHz," *IEEE Transactions on Electromagnetic Compatibility*, vol. 48, no. 4, pp. 634–640, 2006.

[17] S. Fernández Romero, P. López Rodríguez, D. Escot Bocanegra, D. Poyatos Martínez, and M. Añón Cancela, "Comparing open area test site and resonant chamber for unmanned aerial vehicle's high-intensity radiated field testing," *IEEE Transactions on Electromagnetic Compatibility*, vol. 60, no. 6, pp. 1704–1711, 2018.

[18] I. Barbary, J. Schiffner, M. Rozgic, R. Rollan, C. Schlie, J. Storjohann, M. Hagel, L. O. Fichte, S. Potthast, M. Schaarschmidt, S. Lange, and M. Stiemer, "Simulation based analysis of electric field distributions in small reverberation chambers," in *2017 International Symposium on Electromagnetic Compatibility - EMC EUROPE*, 2017, pp. 1–6.

[19] S. Araujo, M. Kazanbas, M. Wendt, T. Kleeb, and P. Zacharias, "Prospects of GaN devices in automotive electrification," in *PCIM Europe 2014; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2014, pp. 1–8.

[20] L. M. Tolbert and B. Ozpineci, "Wide bandgap semiconductors for utility applications," Oak Ridge National Laboratory, Tech. Rep. ORNL/TM-2003/257, 2003, Accessed: December 9, 2022. [Online]. Available: https://info.ornl.gov/sites/publications/Files/Pub57423.pdf

[21] GaN Systems, "GaN switching test measurement techniques," 2018, Accessed: December 9, 2022. [Online]. Available: https://gansystems.com/wp-content/uploads/2018/08/GN003-Measurement-Techniques-for-High-Speed-GaN-E-HEMTs_20180816.pdf

[22] J. Millan, P. Godignon, X. Perpina, A. Perez-Tomas, and J. Rebollo, "A survey of wide bandgap power semiconductor devices," *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2155–2163, 2014.

[23] A. S. Abdelrahman, Z. Erdem, Y. Attia, and M. Z. Youssef, "Wide bandgap devices in electric vehicle converters: A performance survey," *Canadian Journal of Electrical and Computer Engineering*, vol. 41, no. 1, pp. 45–54, 2018.

[24] Infineon, "PCB design guide for XMC1000," Application Note AP32316 Version 2.1, 2016, Accessed: December 9, 2022. [Online]. Available: https://www.infineon.com/dgdl/Infineon-AP32316_XMC1000_PCB_Design_Guide-AN-v02_02-EN.pdf?fileId=5546d46253f6505701543e3d045548b1

[25] B. Zhang and S. Wang, "An overview of wide bandgap power semiconductor device packaging techniques for EMI reduction," in *2018 IEEE Symposium on Electromagnetic Compatibility, Signal Integrity and Power Integrity (EMC, SI & PI)*, 2018, pp. 297–301.

[26] B. Sun, R. Burgos, and D. Boroyevich, "Common-mode EMI unterminated behavioral model of wide-bandgap-based power converters operating at high switching frequency," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 4, pp. 2561–2570, 2019.

[27] F. Sabath, "Modellierung von Szenarien vorsatzlicher elektromagnetischer Beeinflussung," Habilitation, Fakultät für Elektrotechnik und Informatik der Gottfried Wilhelm Leibniz Universität Hannover, 2020, Accessed: December 9, 2022. [Online]. Available: https://www.repo.uni-hannover.de/handle/123456789/10467

[28] N. Mora, F. Vega, G. Lugrin, F. Rachidi, and M. Rubinstein, "Study and classification of potential IEMI sources," *System Design and Assessment Notes, Note 41*, 2014.

[29] EDA-Zentrum, "progressivKI," 2022, Accessed: December 9, 2022. [Online]. Available: https://www.edacentrum.de/progressivki/

[30] A. Mirhoseini, A. Goldie, M. Yazgan, J. W. Jiang, E. Songhori, S. Wang, Y.-J. Lee, E. Johnson, O. Pathak, A. Nazi, J. Pak, A. Tong, K. Srinivasa, W. Hang, E. Tuncer, Q. V. Le, J. Laudon, R. Ho, R. Carpenter, and J. Dean, "A graph placement methodology for fast chip design," *Nature*, vol. 594, no. 7862, pp. 207–212, 2021.

[31] L. Zhang, J. Juang, Z. Kiguradze, B. Pu, S. Jin, S. Wu, Z. Yang, J. Fan, and C. Hwang, "Fast impedance prediction for power distribution network using deep learning," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 35, no. 2, p. e2956, 2022.

[32] S. Zhao, F. Blaabjerg, and H. Wang, "An overview of artificial intelligence applications for power electronics," *IEEE Transactions on Power Electronics*, vol. 36, no. 4, pp. 4633–4658, 2021.

[33] R. S. Sutton and A. Barto, *Reinforcement Learning: An Introduction*, 2nd ed., ser. Adaptive Computation and Machine Learning series. Cambridge, Massachusetts; London, England: The MIT Press, 2018.

Towards a Database for Deriving Design Aspects of Industrial Exoskeletons

Niclas Hoffmann*, Maité Calisti, Benjamin Reimeir, Lennart Ralfs and Robert Weidner
Helmut Schmidt University / University of the Federal Armed Forces Hamburg
Hamburg, Germany
*niclas.hoffmann@hsu-hh.de

Abstract **– Industrial exoskeletons aim to physically support humans in individual support situations. One challenge exists in providing a comfortable fit and an appropriate support for specific users and tasks. As part of the DTEC-research project "EVO-MTI", typical working activities in production and logistics are exemplarily considered. Based on an anonymous description of demographic and anthropometric user data and multicriterial tool-based task analyses, several system requirement specifications are reasonable derivable for certain user groups and task profiles. The gathered aspects are numerically summarized in a database that is planned to be expanded by tasks, users, and body segments within the research project. Overall, this knowledge database represents the coupling element of the project-intended environment for developing and evaluating physical support systems like exoskeletons.**

Keyword – Exoskeleton, Industrial Application, User and Task Analysis, Database

I. INTRODUCTION

Technical support systems are increasingly used in occupational and daily activities to face the raising support demands of humans [1]. Selected general reasons might be the demographic change, increased product diversity and complexity, extended working lives, turnover of employees, and global competitiveness [2].

Industrial exoskeletons are a wearable support technology. They aim to support humans when performing physically demanding tasks [3]. For this, they usually transfer external system forces to the human musculoskeletal system by physical interfaces. However, industrial exoskeletons feature a different morphology (in terms of, e.g., path of force, materials, or actuators) [4, 5] and diverse technical properties (in terms of, e.g., supported body regions, height of support, or support control system) [6]. This causes a variety of possible system designs and a system customization for selected application scenarios [7, 8]. Their suitability is generally determined by aspects from the triad of human, system, and activity [9, 10].

For designing tailored physical support systems, the DTEC-research project "EVO-MTI" [11] aims to establish a design environment for developing and evaluating support systems on the application example of exoskeletons (see FIGURE 1). Its infrastructure distinguishes between three core elements and will mainly enable

1) the simulation and analysis of real application scenarios with mock-ups in a laboratory setting (with and without the use of different exoskeletons),

2) the simulation and analysis of exoskeletal properties with collaborative robots, as well as

3) the simulation of system users and the evaluation of exoskeletons with a humanoid or human-like testing machine.

Within the project period, different gathered data and derivable insights will be integrated into a coupling knowledge database for future decisions on system evaluations, optimizations, and designs. Accordingly, this emerging tool offers potential to revolutionise, ease, and improve the development process of physical support systems like exoskeletons.

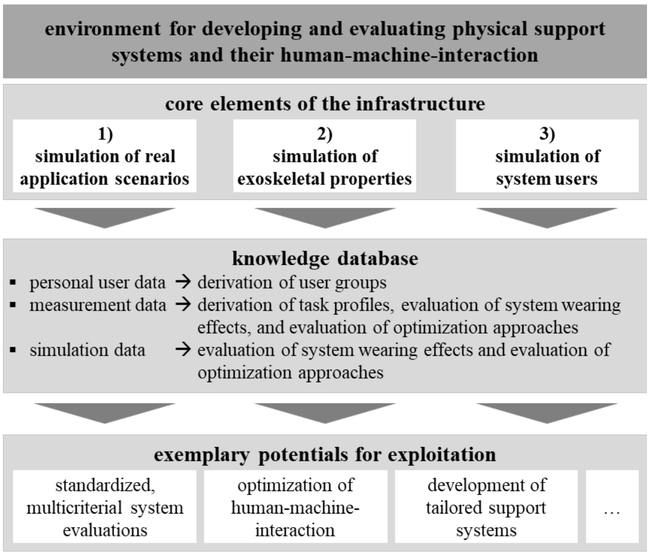


FIGURE 1: OVERVIEW OF THE INTENDED DESIGN ENVIRONMENT FOR DEVELOPING AND EVALUATING PHYSICAL SUPPORT SYSTEMS.

This paper mainly refers to the first aspect of "EVO-MTI" – the simulation of real application scenarios in a laboratory set-up, the structured storage of relevant acquired data into the knowledge database, and the derivation of required design characteristics of functional elements. It aims to reasonably define objective system requirements for the addressed use case, which is basically the first step of the transdisciplinary development approach of Weidner et al. [12]. FIGURE 2 summarizes the intended procedure for deriving these design aspects. It can be roughly divided into the phases of data acquisition, data analysis and processing, and exoskeleton development. In the following, the focus of the paper exemplarily lies on shoulder support systems. The use cases analysed and the database excerpts shown are also geared towards this exemplary application.

https://doi.org/10.24405/14549

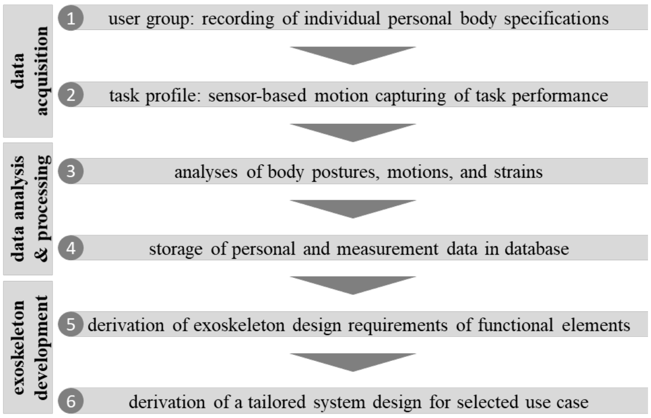


FIGURE 2: OVERVIEW OF THE PROCEDURE FOR DERIVING TAILORED SUPPORT SYSTEMS IN THE CONTEXT OF CORE-ELEMENT 1.

II. DATA ACQUISITION

This phase contains the data acquisition of the user group (step 1) and task performances (step 2) as fundamental basis of and relevant information for the database.

A. *Selected user group*

To demonstrate the general relations and functions of the database, an exemplary user group is consulted and consists of three test subjects (two males, one female). The selected test subjects feature a visible variance in body shape. Their demographic and anthropometric data are detailly summarized in TABLE I. The abbreviation “F” and “M” stands for “Female” and “Male”, respectively. The dominant hand can be “Left” (“L”) or “Right” (“R”). For anthropometric measurements, a measuring tape is used. The shoulder width is measured from the left to the right lateral edge of the acromion. The span is determined with laterally stretched arms from the left to the right wrist and elbow, respectively. The upper body length describes the distance from trochanter major at the hip to processus spinosus at C7. The upper arm perimeter is measured at biceps head. The pelvis perimeter is determined at the iliac crest.

TABLE I: DATASET OF TEST SUBJECTS.

criterion	***test subjects***		
	ID1	***ID2***	***ID3***
gender	F	M	M
age [years]	27	27	25
height [cm]	171.0	175.0	185.0
dominant hand	R	R	R
weight [kg]	72.7	85.0	72.0
shoulder width [cm]	35.7	41.0	41.5
wrist span [cm]	127.8	132.0	145.5
elbow span [cm]	83.3	83.0	92.5
upper body length [cm]	62.2	67.0	65.2
upper arm perimeter [cm]	25.5	32.0	27.0
pelvis perimeter [cm]	89.0	98.5	81.0
chest perimeter [cm]	89.0	104.0	93.0

A. *Selected task profiles*

In principle, there is a vastness of tasks in occupational and daily life, where exoskeletons are applicable. Within the exemplary investigation in this paper, the considered scenario is tailored on the production and logistics sector, and particularly on applications with mainly activities at head level or above. The task selection basically takes up task profiles of the developed test course of Ralfs et al. [13] that aggregated representative industrial tasks with similar characteristics to coherent clusters. This paper considers the tasks “overhead torquing”, “grinding walls”, and “clamping pipes”. All tasks are displayed in FIGURE 3. The task selection considers diversity in motion, handled load, dynamics, handedness, and working height. All tasks are executed without wearing an exoskeleton.

Task A: Overhead torquing. In this task, the test subject holds an electric screwdriver (weight: approx. 2.55 kg) in the dominant hand and fastens a pre-fixed screw into a wooden beam at overhead level. The dominant arm is dynamically lifted and lowered from hip height to the wooden beam for each torquing. The height of the beam is individually adjusted so that each test subject has approximately around 90° shoulder and elbow flexion. Each test subject performs one repetition.

Task B: Grinding walls. In this task, the test subject holds a drywall grinder (weight: approx. 5.0 kg) in both hands and dynamically leads its head on a defined linear path and in a dominant direction of movement at the ceiling. The dominant hand is positioned in the middle and the non-dominant hand at the end of the handlebar. Each test subject performs four repetitions.

Task C: Clamping pipes. In this task, the test subject clamps a garden hose (weight: approx. 0.15 kg) with both hands in defined fixtures on a wooden board at overhead level. The task is comparatively static since both hands remain elevated above head level for a longer time. The height of the wooden board is individually adjusted so that it remains reachable for every test subject with almost stretched arms. The task is finished when ten clamps are fixed.

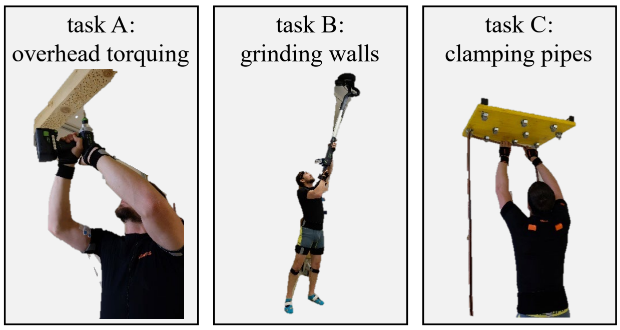


FIGURE 3: PERFORMED TASKS IN LABORATORY SETTING.

B. *Applied motion capture method*

The motion capture of each test subject is done with the system “MVN Awinda Analyze Pro” (Version: 2021.0.1) by Xsens [14]. It works with 17 inertial sensors that are fixed on defined body segments on head, torso, upper limbs, and lower limbs. Based on anthropometric input data of the respective test subject and an initial calibration, the system’s software application compiles an individual digital human anatomical body model and calculates the kinematics of body segments.

III. DATA ANALYSIS AND PROCESSING

After successful user- and task-related data acquisition, this section describes the processing steps for analysing (step 3) and their storage in the knowledge database (step 4). Xsens is supplemented with the analytical software "INDUSTRIAL ATHLETE" (Version: 1.93.6) by scalefit [15]. This software builds upon the anatomical body model of Xsens and enables body strain analyses by considering the mass of body segments (based on measured body segment dimensions and a simulated body model) and hand-held loads.

C. Analyses of body postures, motions, and strains

FIGURE 4 displays the curves of shoulder flexion angles and shoulder joint torques for every task performed by test subject ID 3, since shoulder-supporting exoskeletons mainly address the support of this arm motion. A comprehensive overview of additional joint angles and torques could be added and would broaden the biomechanical representation of the specific tasks.

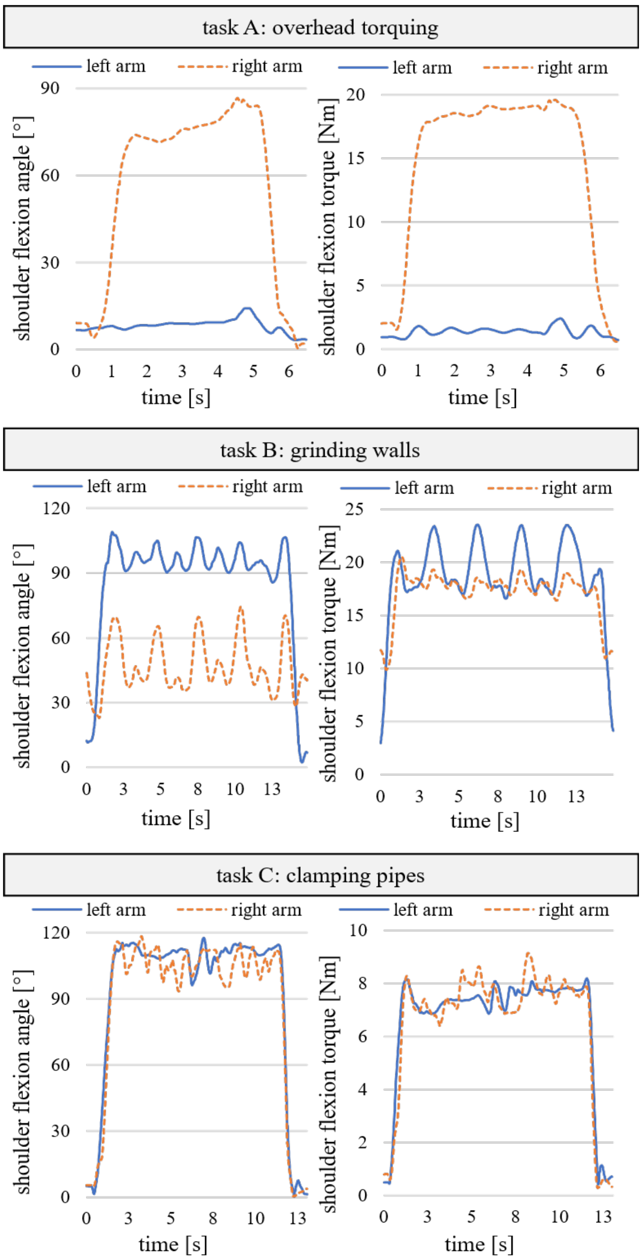


FIGURE 4: SHOULDER FLEXION ANGLES (LEFT) AND TORQUES (RIGHT) OF A SINGLE TEST SUBJECT (ID 3) PERFORMING TASK A - C.

FIGURE 5 displays the shoulder joint torques of all test subjects (ID 1-3) performing the same task (task A). As can be seen, variability in movement execution, speed, and body segment dimensions can lead to high variability in joint loads.

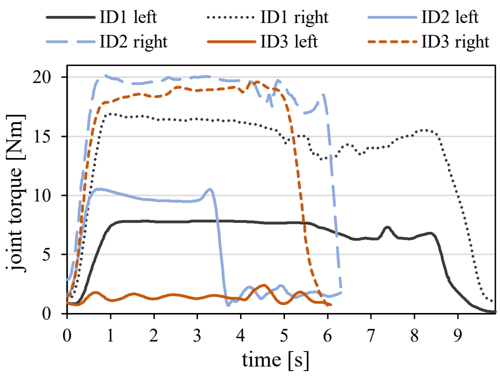


FIGURE 5: SHOULDER JOINT TORQUE FOR ALL TEST SUBJECTS (ID 1 - 3) PERFORMING TASK A (OVERHEAD TORQUING).

D. Storages into knowledge database

The relevant demographic and anthropometric data of the analysed user group and characteristics of task execution are stored in the knowledge database. To enable a simple data handling and further editing, the relational database mainly consists of numerical or binary parameters. Subscripted identification tags of analysed user groups and tasks are used to reach clarity, readability, and mapping. It is recommendable to work with individual codes like abbreviations, initials, and dates of investigations, so that a clear but data privacy compliant correlation is assured.

Table I contains the demographic and anthropometric dataset of every test subject. Based on this, Table II aggregates these data and summarizes the information of the analysed user group in total. The data are given with mean value ± standard deviation [minimum value; maximum value]. $U_{I:\,A,\,B,\,C}$ describes the values of user group I that performs the tasks A, B, and C.

TABLE II: DATASET OF USER GROUPS.

criterion	***user groups*** $U_{I:\,A,\,B,\,C}$
number of males	2
number of females	1
dominant hand	3 x R, 0 x L
age [years]	26.3 ± 0.9 [25; 27]
height [cm]	177.0 ± 5.9 [171.0; 185.0]
weight [cm]	72.2 ± 9.8 [61.0; 85.0]
shoulder width [cm]	39.4 ± 2.6 [35.7; 41.5]
wrist span [cm]	153.1 ± 7.6 [127.8; 145.5]
elbow span [cm]	86.3 ± 4.4 [83.0; 92.5]
upper body length [cm]	64.8 ± 2.0 [62.2; 67.0]

criterion	user groups
	$U_{I: A, B, C}$
upper arm perimeter [cm]	28.2 ± 2.8 [25.5; 32.0]
pelvis perimeter [cm]	89.5 ±7.2 [81.0; 98.5]
chest perimeter [cm]	95.3 ± 6.3 [89.0; 104.0]

TABLE III summarizes relevant characteristics of the analysed task profiles performed by the user group $U_{I: A, B, C}$. It is done separately since task performances and body strains can differ between tasks (see FIGURE 4). Since values and curves can differ between test subjects (see FIGURE 5), the data is given with mean value ± intersubject variability. $T_{I: A, B, C: A}$ describes the values of user group I: A, B, C that performs the task A "overhead torquing". The shoulder kinematics are given for shoulder flexion and extension. Here, the maximum values can either arise when lowering or rising the arm. The extrapolated task repetition assumes an eight-hour-workshift without breaks. The further information values are coded as follows:

- The core activity has a dropdown menu of 1) "lifting / carrying", 2) "push / pull", 3) "screwing / drilling", or 4) "holding / stabilising".
- The working position can be differentiated in 1) "kneeling / squatting", 2) "upper body bending", 3) "upright standing", 4) "upright racking", 5) "sitting", or 6) "lying".
- The handedness can be 1) "singular", 2) "equally bi-manual", or 3) "unequally bi-manual".
- The room temperature can be 1) "< 10°C", 2) "10°C - 19°C", 3) "19-24°C", or 4) "> 24°C".
- The relative room humidity can be 1) "< 30%), 2) "30-60%", or 3) "> 60%".
- The regulation of personal protective equipment can be 1) "yes" and 2) "no".
- The available working space can be 1) "< 0.5 x 0.5 m²", 2) "0.5 x 0.5 m² - 1.2 x 1.2 m²), or 3) > 1.2 x 1.2 m²".

It should also be noted at this point that both some criteria in the database and their parameter values can vary for different use case scenarios.

TABLE III: DATASET OF TASK CHARACTERISTICS.

criterion	tasks		
	$T_{I: A, B, C: A}$	$T_{I: A, B C: B}$	$T_{I: A, B, C: C}$
shoulder flexion angle range [°]	L: 71.3 ± 50.4 R: 85.8 ± 7.4	L: 109.4 ± 16.0 R: 35.7 ± 11.3	L: 130.3 ± 22.1 R:121.6 ± 14.1
shoulder flexion torque peak [Nm]	L: 6.9 ± 4.1 R: 18.7 ± 1.5	L: 22.9 ± 2.8 R: 19.6 ± 1.2	L: 8.9 ± 1.8 R: 9.1 ± 2.1
max. shoulder joint acceleration [°/s²]	L: 713.4 ± 534.7 R: 511.7 ± 126.7	L:539.8 ± 240.1 R:420.4 ± 293.5	L:842.9 ± 117.2 R:809.8 ±104.9
max. shoulder joint velocity [°/s]	L: 129.6 ± 125.6 R: 118.1 ± 13.8	L: 140.2 ± 36.3 R: 64.7 ± 33.0	L: 155.2 ± 6.5 R:145.3 ± 19.7
single task duration [s]	7.5 ± 2.5	15.4 ± 2.3	14.6 ± 2.3
task frequency [1/min]	8.0	3.9	4.1

criterion	tasks		
	$T_{I: A, B, C: A}$	$T_{I: A, B C: B}$	$T_{I: A, B, C: C}$
extrapolated number of task repetitions	3,840	1,872	1,968
handheld load [kg]	2.55	5.00	0.15
core activity	3	4	2
working position	3	3	4
handedness	1	3	2
working distance [m]	0	0	0
room temperature	3	3	3
room humidity	2	2	2
personal protect-ive equipment	2	2	2
working space	3	3	3

IV. EXOSKELETON DEVELOPMENT

This section contains the derivation of exoskeletal design aspects of functional elements (step 5) based on the stored datasets of user groups and tasks. At this point, a concrete technical transfer guide for designing a tailored exoskeleton (step 6) is not intended since the exoskeletal design lately depends on individual design opinions, several technical and regulatory restrictions, and further circumstances. However, TABLE IV presents an abstract correlation of database criteria and functional design elements of a shoulder-supporting exoskeleton. It aims to address main exoskeletal design aspects like fit and adaptability, motion and movability, and support characteristics and shows which criteria can influence the respective design aspects of exoskeletons.

TABLE IV: SELECTION OF DERIVABLE EXOSKELETAL DESIGN ASPECTS.

exoskeletal design element	design aspect	related database criterion
structure	path of force (scope, size, adjustability)	• size and variabilty of body segments (i.e., shoulder width, upper arm length, upper body length) • maximum shoulder torque • handheld load • core activity • working position • handedness • personal protective equipment • working space
	material (rigidity, weight)	• maximum shoulder torque • handheld load • working distance
	degrees of freedom	• shoulder angle range • core activity • working position
	body proximity	• working position • personal protective equipment • working space
physical interfaces	position (lever arm)	• maximum shoulder torque • core activity • working position • personal protective equipment • working space
	shape	• sizing of body segments (i.e., upper arm perimeter, pelvis perimeter, chest perimeter) • maximum shoulder torque • handheld load • personal protective equipment

exoskeletal design element	*design aspect*	*related database criterion*
	material (breathability, padding)	• maximum shoulder torque • room temperature • room humidity
actuators	power	• maximum shoulder torque • handheld load
	capacity	• (extrapolated) task duration • task frequency • core activity
	dynamics	• maximum shoulder joint acceleration • maximum shoulder joint velocity • task duration • task frequency
	adaptability	• shoulder angle range • maximum shoulder torque • maximum shoulder joint acceleration • maximum shoulder joint velocity
	workspace	• shoulder angle range
	number	• handedness

In the following, some abstract examples for deriving objective design requirements of selected functional elements of a shoulder-supporting exoskeleton are given:

- Concerning the functional element "structure" and in particular the "path of force", the mean size and variability of single body segments of the user group hint the needed total size and adjustability of the kinematic back and shoulder structure.
- The intended level of support in reference to the occurring maximum shoulder torque helps determine its scope like direct flux from feet or hip to upper arm or hand-held tool. A redundant information about the intended level of support can be derived by the weight of the handheld load.
- The handedness and maximum shoulder torque of each arm can determine the necessity of having a support on both arms as well.
- Concerning another functional element like the actuator, its required power can be defined by the intended support level based on the handheld load or maximum shoulder joint. Its capacity can be determined by the daily operating time or the daily number of movements. For instance, passive actuators can be preferable for stabilizing tasks, whereas active actuators are more comfortable in dynamic tasks with frequent arm rising and lowering, which can potentially minimize the work effort against the system's support when lowering the arm. The latter might also be preferable for varying tasks and users with different working postures and support needs since support levels can easily be adjusted.

Finally, it is always recommendable to consider occurring joint angle and body strain progressions over time (see graphs in chapter 3.1) in addition to the numerical values in the database. This will enable a design of individual- or task-orientated appropriate support curves [16] in relation to, e.g., the shoulder joint angle and occurring body strains. Besides, the database can be supplemented by gathered data of the second aspect of the project, the simulation of exoskeletons with collaborative robots, as well as of the third aspect, the simulation of system users with a humanoid or human-like testing machine (see FIGURE 1). Both will provide valuable additional design information.

V. DISCUSSION

In this paper, the knowledge database with its procedure for data collection and derivation of objective design aspects for industrial exoskeletons based on simulations of real applications (see core element 1 in FIGURE 1) is presented on an exemplary level in terms of analysed user groups, tasks, and the addressed body segment. Even though it is neither representative nor comprehensive, the approach contributes to generally specify exoskeletal system requirements. At this point, it shows the potential of deriving selected, objective aspects and guidelines for designing shoulder-supporting exoskeletons due to a better comprehension of the addressed support situation with its representative characteristics. For this, the pursued inverse dynamics approach of "INDUSTRIAL ATHLETE" for calculating body strains is sufficient in terms of the calculation accuracy for the required database information as well as some aspects are in parts redundantly listed in the database in a different form of description or concreteness for designers. There is potential for exploiting the information collected in a structured manner in the database, for example with regard to carrying out a system evaluation, improving human-machine interaction, or developing tailored support systems. Though, any further dealing as well as the technical transformation and interpretation of respective database criteria still remain on an individual and creative level for designers. Similarly, the pure knowledge of system requirements cannot guarantee a reasonable technical realization of exoskeletal design elements. All in all, it is planned that the derived datasets and insights of core element 1 will be restored to the intended design environment (see core elements 2 and 3 in FIGURE 1) so that synergetic effects for developing tailored support systems to users and tasks will appear within the remaining project period.

ACKNOWLEDGEMENT

This content is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project EVO-MTI: Digitale Entwicklungs- und Validierungsumgebung für physische Unterstützungssysteme zur Optimierung der Mensch-Technik-Interaktion (MTI) und -Schnittstellen am Beispiel von Exoskeletten].

REFERENCES

[1] R. Weidner and A. Karafillidis, 'Distinguishing Support Technologies. A General Scheme and its Application to Exoskeletons', in *Developing Support Technologies. Biosystems and Biorobotic.*, Cham, Switzerland: Springer, 2018.

[2] R. Weidner, T. Redlich, and J. P. Wulfsberg, 'Technische Unterstützungssysteme', Berlin Heidelberg: Springer Verlag, 2015.

[3] M. P. de Looze, T. Bosch, F. Krause, K. S. Stadler, and L. W. O'Sullivan, 'Exoskeletons for industrial application and their potential effects on physical work load', *Ergonomics*, vol. 59, pp. 1–11, 2016, doi: 10.1080/00140139.2015.1081988.

[4] S. Fox, O. Aranko, J. Heilala, and P. Vahala, 'Exoskeletons: Comprehensive, comparative and critical manufacturing performance', *J. Manuf. Technol. Manag.*, vol. 31, no. 6, pp. 1261–1280, 2019, doi: 10.1108/JMTM-01-2019-0023.

[5] R. A. R. C. Gopura, D. S. V. Bandara, K. Kiguchi, and G. K. I. Mann, 'Developments in hardware systems of active upper-limb exoskeleton robots: A review', *Rob. Auton. Syst.*, vol. 75, pp. 203–220, 2016, doi: 10.1016/j.robot.2015.10.001.

[6] R. Weidner, C. Linnenberg, N. Hoffmann, G. Prokop, and V. Edwards, 'Exoskelette für den industriellen Kontext: Systematisches Review und

Klassifikation', *66. Kongress der Gesellschaft für Arbeitswissenschaften*, 2020.
[7] S. Crea *et al.*, 'Occupational exoskeletons: A roadmap toward large-scale adoption. Methodology and challenges of bringing exoskeletons to workplaces', *Wearable Technol.*, vol. 2, 2021, doi: 10.1017/wtc.2021.11.
[8] L. Ralfs, N. Hoffmann, and R. Weidner, 'Approach of a Decision Support Matrix for the Implementation of Exoskeletons in Industrial Workplaces', in *Annals of Scientific Society for Assembly, Handling and Industrial Robotics 2021*, T. Schüppstuhl, K. Tracht, and A. Raatz, Eds. Cham: Springer, 2022, pp. 165–176.
[9] R. Weidner, N. Kong, and J. P. Wulfsberg, 'Human Hybrid Robot: A new concept for supporting manual assembly tasks', *Prod. Eng.*, vol. 7, no. 6, pp. 675–684, 2013, doi: 10.1007/s11740-013-0487-x.
[10] N. Hoffmann, L. Ralfs, and R. Weidner, 'Leitmerkmale und Vorgehen einer Implementierung von Exoskeletten', *Zeitschrift für wirtschaftlichen Fabrikbetr.*, vol. 116, no. 7–8, 2021, doi: 10.1515/zwf-2021-0099.
[11] Dtec.bw, 'EVO-MTI - Umgebung zur Entwicklung für phys. Unterstützungssysteme'. https://dtecbw.de/home/forschung/hsu/projekt-evo-mti (accessed Aug. 26, 2022).
[12] R. Weidner, A. Argubi-Wollesen, A. Karafillidis, and B. Otten, 'Human-Machine Integration as Support Relation: Individual and Task-Related Hybrid Systems in Industrial Production', *i-com*, vol. 16, no. 2, pp. 143–152, 2017, doi: https://doi.org/10.1515/icom-2017-0019.
[13] L. Ralfs, N. Hoffmann, and R. Weidner, 'Method and test course for the evaluation of industrial exoskeletons', *Appl. Sci.*, vol. 11, no. 9614, pp. 1–19, 2021, doi: 10.3390/app11209614.
[14] XSens, 'MVN Analyze'. https://www.xsens.com/products/mvn-analyze (accessed Aug. 26, 2022).
[15] scalefit, 'INDUSTRIAL ATHLETE'. https://www.scalefit.de/home.html#industrial-athlete (accessed Aug. 26, 2022).
[16] O. Ott, L. Ralfs, and R. Weidner, 'Framework for qualifying exoskeletons as adaptive support technology', *(under Review).*

Free Jazz on the Battlefield

How GhostPlay's AI Approach Enhances Air Defense

Heiko Borchert*
Co-Director Defense AI Observatory
Helmut Schmidt University
University of the German Armed Forces
Hamburg, Germany
*hb@defenseai.eu

Christian Brandlhuber*
21strategies
Munich, Germany
*christian.brandlhuber@21strategies.com

Armin Brandstetter*
Hensoldt Sensor Systems
Ulm, Germany
*armin.brandstetter@hensoldt.net

Gary S. Schaal*
Co-Director Defense AI Observatory
Helmut Schmidt University
University of the German Armed Forces
Hamburg, Germany
gschaal@hsu-hh.de

***Abstract* – Current conflicts underline the importance of Integrated Air Defense Systems (IADS) to keep aggressor air power at distance and ensure allied freedom of maneuver. But what happens if aggressors saturate, deceive, and neutralize allied air defense with hundreds of unmanned aerial assets in conventional attrition attacks or apply hitherto unknown tactics potentially enhanced by artificial intelligence (AI)? That's the question GhostPlay addresses by developing defense decision algorithms (= Play) to support tactical military decision-making against aggressors that operate at different levels of ambition, excel at leveraging unknown and emerging tactics, and strive to exploit operational tempo to their benefit. GhostPlay uses a synthetic simulation environment (= Ghost) to assess if and to what extent AI-enhanced solutions – operating in stand-alone or federated systems – can be used to accelerate operational tempo, enhance tactical level performance, and step-up efforts to anticipate future adversarial behavior. Against the background of a growing body of literature on defense innovation, the paper discusses GhostPlay's goal to develop context and consequence-aware AI systems that exploit novel tactics to ensure and scale IADS-based protection. The paper sheds light on GhostPlay's conceptual and technical setup, summarizes initial simulation-based findings and outlines future development options.**

Keyword – Defense Artificial Intelligence, emergent behavior, multi-agent systems, swarm logic, tactical versatility.

Nomenclature

A2AD	Anti-Access/Area Denial
AAA	Anti-Aircraft Artillery
AD	Air Defense
AI	Artificial Intelligence
C2	Command and Control
C4	Command, Control, Computers, Communications
DARPA	Defense Advanced Research Projects Agency
DecPOMDP	Decentralize Partially Observable Markov Decision Process
EmCon	Emission Control
EW	Electronic Warfare
FlkPz	Flakpanzer
HARM	High-Speed Anti-Radiation Missile
HVA	High Value Asset
IADS	Integrated Air Defense
JTFS	Joint Tactical Fire Support
MDP	Markov Decision Process
OODA	Orient, Observe, Decide, Act
POMDP	Partially Observable Markov Decision Process
RAP	Recognized Air Picture
RL	Reinforcement Learning
ROE	Rules of Engagement
SHORAD	Short-Range Air Defense
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
VBE	Value-Based Engineering
VSHORAD	Very Short-Range Air Defense

https://doi.org/10.24405/14550

I. If Innovation Is the Solution, What Is the Problem?

"Military Innovation" has become a hot buzzword among NATO and EU members. Two forces shape this current defense innovation discourse. First, increasingly assertive adversarial military capabilities underline the need for allied defense innovation to keep the upper hand vis-à-vis strategic competitors [1]. Second, the defense innovation discourse emphasizes the important role of emerging technologies like artificial intelligence (AI), autonomous and robotic systems, space, and quantum technologies to name but a few examples [2]. In most cases, commercial entities that are not yet part of the defense ecosystem are frontrunners in developing and applying these technologies. This increases the need to integrate new players, technologies, and underpinning capacities into the defense industrial and technology base.

Although in fashion, defense innovation is notoriously difficult to define [3]. Few capstone documents describe precisely what type of innovation armed forces are expected to deliver and what needs to change to accomplish the respective tasks. Based on [4] we contend that defense innovation describes conceptual/cultural, organizational, and technological novelties that change how armed forces prepare for and conduct the application of military power. In so doing, armed forces build on past operational experience and requirements.

Against the background of these three vectors, GhostPlay's innovation understanding is two-fold. First, GhostPlay addresses a pressing gap as Suppression of Enemy Air Defense (SEAD) capabilities have atrophied in most EU/NATO nations since the end of the Cold War. We explore to what extent AI-based solutions can augment swarms of unmanned aerial vehicles (UAV) to conduct SEAD missions. Second, GhostPlay does not look at new technologies to augment existing technologies. Rather we look at ways in which the use of new technology triggers novel battlefield behavior at the tactical level. With these two aspects in mind, GhostPlay models novel AI-based solutions for air defense (AD) and aggressor swarms that learn how to outperform each other. The first project phase, which we discuss in this paper, focuses on the defender.

To model and learn superior tactical AD behavior that withstands and counters UAV swarms, we consider two main aspects. First, in most recent conflicts UAVs gained the upper hand against AD as AD solutions have been brittle [4]. Brittleness results from a lack of proper integration of all relevant sensors and effectors to create a powerful AD federation. Integration, in turn, requires coordination. This is where the second element kicks in. GhostPlay focuses on novel approaches that increase tactical AD versatility to fend-off aggressors. In so doing, GhostPlay breaks new ground by exploring options to develop federated AD webs that coordinate single entities like sensors and effectors through emergent behavior without the help of central and hierarchical command and control (C2) solutions. As we explain in section II.B, GhostPlay bakes the C2 capability into every element of the AD web rather than delegating C2 to a dedicated system, that adversaries can target and attack. This approach makes the AD web much more fluid, agile, and resilient in responding to threats and mission requirements.

Superior tactical versatility augments military freedom of action. To this purpose GhostPlay seeks to leverage the principles of war that guide and inform how military power is applied [5]. Among other things, GhostPlay strives for

- economy of effort by optimizing the use of effectors in time and place as well as with respect to how force is organized to achieve optimal effects under any given conditions;
- surprise by using emergent behavior in a way that produces tactical behavior not yet witnessed by aggressors;
- initiative by anticipating future adversarial moves with the goal to preemptively position allied force to engage adversaries.

In sum, GhostPlay contributes to defense innovation by developing technology that enables novel battlefield behavior to enhance tactical versatility, first, for air defenders and, at later stages, also for UAV swarms performing SEAD missions. In this regard, GhostPlay's innovation is like free jazz as it improvises, responds to external stimuli, is dynamic, and integrates whatever asset is available to accomplish the AD mission by leveraging a new generation of coordination mechanisms that are context and consequence aware.

II. GhostPlay's Novelty: Free Jazz vs. Central Coordination

While GhostPlay strives to create innovation in terms of tangible advantages and capability improvements for future AD concepts, the project's underlying technology contributes to one of the most challenging topics in contemporary AI research, the ability to learn tactical behavior in cooperation with other machines and/or humans. This entails three capabilities. First, the capability to properly assess a situation and anticipate adversarial behavior. Second, the capability to learn how to orchestrate and organize a system's action to achieve objectives across time-extended scenarios and in response to enemy action. This also includes the ability to assess, how the relevant environment may respond to the defense system's actions. Third, the capability to motivate a system to learn on its own when and how to cooperate to solve complex tasks with partners. These capabilities underpin future solutions striving for technical autonomy in machine-to-machine and machine-to-human interaction.

Right now, the idea that Deep Reinforcement Learning solutions like AlphaGo, Alpha Star or Open AI have super-human capabilities creates quite a hype. But these systems play computer games in a well-known and completely stable environment. Military solutions, by contrast, operate in a non-stationary real-world environment, where unforeseen incidents occur. Moreover, commensurate with adversarial intentions and capabilities, the rules of the military game can change quite quickly.

This is the environment in which GhostPlay is supposed to operate. Integrated Air Defense Solutions (IADS) adopt a layered approach (Figure 1). Sensor and effector reach is the discriminator that helps setting up Very Short Range Air Defense (VSHORAD), Short Range Air Defense (SHORAD), Medium Range Air Defense (MRAD) and long-range defensive ground-based "domes."

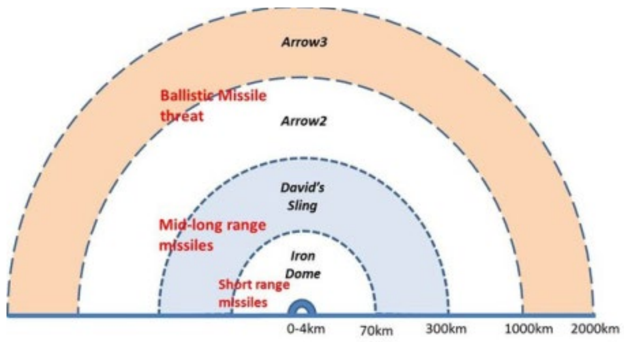


FIGURE 1: LAYERED APPROACH TO AIR DEFENSE. SOURCE [10].

Today, specific systems integrate different sensors and effectors for each "dome." Each system is developed in isolation. The governing principle to achieve integration is hierarchical and centralistic: Central command and control (C2) runs each system, which report into a hierarchic structure with nodes that coordinates multiple launchers. Ultimately, a high-level C2 or C4 system (Command, Control, Communications and Computers) integrates and coordinates all elements. Although tried and tested, this set up remains static, is quite brittle and often leads to unsatisfactory sensor-to-effector latency.

Contemporary state-of-the art solutions may use AI to improve individual processing steps in the observe-orient-decide-act cycle (OODA). GhostPlay goes beyond the automation of individual steps in the OODA workflow. Rather, GhostPlay policies establish a fine granular and forward-looking stochastic optimal control regime, while substantially accelerating decision-making and reducing sensor-to-effector latency.

The GhostPlay architecture achieves this by mediating multiple concurrent control processes ("agent"), each implementing a specialized control strategy ("policy"), for example, to effectively control a physical system, like sensors and effectors, or to determine a certain action plan. GhostPlay's agents are not centrally coordinated. Rather they use common behavioral conventions ("rules of encounter") to ensure mediation and information exchange while training to achieve a common objective in tandem with partners (multi-agent learning). In contrast to existing AD solutions, GhostPlay has no pipelined data-fusion process on the platform; rather a combined situational picture emerges over time via policies that have learned how to cooperate. This specific design choice has been motivated by the ambition to explore if defense solutions can be developed as emergent systems.

A. Tactical AI: Basic Building Blocks

1) State of the art defense AI

Currently, state of the art defense AI focuses on introducing AI techniques or AI-based components to support individual OODA stages. For example, current applications detect and classify objects in aerial reconnaissance pictures or classify characteristics in the electromagnetic spectrum to infer a potential emitter. In so doing, the OODA loop implements (linear) pipeline processing. Thus, it is sufficient that deployed AI systems only implement a single-step decision. For example, an optical sensor acquires an image or a single video frame, if the sensor streams video sequences (observe); this image is sent to an AI component that tries to detect and classify objects (orient); detected objects will be sent further down the pipeline for identification, and finally arrive at a decision to complete the cycle. The AI component can be interpreted as a Bayesian classifier, which determines the probability that a certain (known) object is present based on the input image and the parameters the AI component has learnt, in most cases weights of a neural network. Currently, the AI classifier thus implements a one-step input-to-output mapping.

2) Improve classification and identification in non-benign environments and fog-of-war

In most real-world applications, in which environmental effects cannot be controlled,[1] or – even worse – if the sensor must operate in a non-benign environment, better results can be obtained, if classification is integrated in a context-aware sensor control strategy (policy): The optical sensor acquires an image, which shows multiple objects. As these objects are far away from the observer they only appear as unspecific pixels on the image. A state-of-the-art AI classifier approach would have to classify each picture and would most simply ignore these target pixels.[2] By contrast, a policy-based sensor management system has different options: Based on the input image, the policy may decide to zoom-in on those pixels which are presumed to represent potential targets or threats that require additional sensor input for classification. The system might even decide to illuminate the position of interest to obtain better information, for example, if clouds obscure the respective objects. This approach would enable the system to provide stable classifications early on and long before the state-of-the-art approach would even be able to recognize the object.

It is very important to note the difference between these two approaches: Interlacing sensor management with classification and identification requires the system not only to learn input-to-output mapping as current AI deployments do. Rather the system needs to learn courses of actions to understand how to achieve good classification results as efficiently as possible. To learn good action sequences, the system must specifically learn to understand the instant effects of an action as well as possible long-term consequences. From a mathematical viewpoint this is no longer a Bayesian classification task, but requires solutions based on the mathematical framework of a Markov Decision Process (MDP).[3]

3) Learn important trade-offs to maximize effectiveness and minimize own-ship exposure/risk

In addition to understanding the instant impact of a specific action, learning good policies also implies that the system learns how to make important trade-offs. Zooming-in on a position, for example, reduces the observation window and might lead to a situation where the system "gets stuck" on pedantically classifying one object, while not recognizing that a fast-moving threat is heading towards the system outside of its observation window. The system also needs to carefully

[1] Industrial environments typically try to create controllable environmental conditions such as lighting. For example, objects that come down a conveyer are always sensed in the same light to limit/exclude negative external effects on conveyor belt transportation.

[2] Note, that this is not the result of a bad classifier but rather results from the fact that it is not possible to classify the targets with the given sensor input.

[3] As the system perceives its environment through sensors and thus only has imperfect perception, we cannot assume to correctly observe the true states of the MDP. Rather we estimate and partially reconstruct the true state from the sequence of observations made so far, which further complicates the task into a Partially Observable Markov Decision Process (POMDP).

balance short-term success with long-term consequences: For example, deciding to illuminate a target with an active radar sensor may satisfy a short term information need but can put the observer at risk as the radar signal emitter may be detected by the target, which in turn may fire a high-speed anti-radiation missile (HARM) to destroy the observer.[4][5] If the benefits of using an active sensor are bigger than the risks very much depends on the situational context. Moreover, the decision to use the active sensor directly affects how the situation will evolve. Systems that master this complexity are context-sensitive and consequence aware and constitute so called 3rd wave AI systems according to the US Defense Advanced Research Projects Agency (DARPA).[6]

Most often Deep Reinforcement Learning is used to train these systems, but this creates technical challenges. Take AI concepts for classification as an example. There is a tutorial input (e.g., tagged example) for each decision made by the system after each round of classification. But there is no immediate feedback to the system, which allows the system to understand whether the respective decision influenced the scenario in a positive or negative way.[7] Although the system needs to maximize the long-term reward intake, the missing link suggests that positive or negative decision outcomes will only be known at the end of the scenario. This, however, can involve several thousand decision steps into the future, which means that the system may get out of sync with the proper function it is expected to accomplish.

4) *Create good initial policies without large databases*

There are concepts in reinforcement learning training protocols that collect traces through scenarios to aggregate so called state-values $V(s)$ or state-action values $Q(s,a)$. These concepts show, if – on average – selecting action a when in state s has been good or bad. Based on these results neural network structures are trained to represent the respective value functions. However, using only these concepts in practice may lead to (very) sub-optimal policies, because the positive or negative outcome of selecting action a in state s not only depends on the current state, but also on the policy that guides future actions. For example, a tracking radar is switched on to illuminate a target and gain accurate position and movement estimates for engagement. This decision may be positive if the threat is successfully intercepted. But it can also be negative in case of failure as the system has exposed its position and created an opportunity for adversarial attack. Moreover, using less precise passive sensors to preassign targets while reducing exposure time would have improved tactics. To gradually converge to good policies, reinforcement learning systems need to strike a balance between exploiting past behavior and exploring new behavior that could deliver novel policies.

With scenarios spanning thousands of decision steps, finding good policies becomes combinatorically prohibitive. This creates specific issues during early training phases. In almost all cases, in which applications have been said to have "superhuman" decision-making capability, initial policies used to start reinforcement improvements have been developed with supervised learning. Supervised learning, in turn, was possible because large databases of expert level policies were available to create tutorial input. But the military application area addressed by GhostPlay, lacks the respective databases. That's why GhostPlay needed to find a way to create initial good policies without databases.

Today, GhostPlay implements a novel "search-in-policy-space technique" to achieve this objective. We decided to initially model an air defense platform, which has multiple on-board sensors and one effector. Each sensor and effector has its own policy, which learns how to optimally use the sensor's specific characteristics. Data is exchanged via a central on-platform long-term memory structure, from which all policies can read and to which all policies can write. Cooperation amongst the policies is mediated by a stigmergic signal. As expected, the resulting platform behavior is rather complex and adapts to fine nuances of an emerging scenario.

B. *Emergence: Cooperative behavior paves the ground for technical autonomy*

Success in joint problem solving very much depends on the way in which perception and interaction with other agents in the team are modeled. As discussed above, a classical AD setup collects and propagates information via different sensors to a central C2 node, where information is aggregated, fused and appropriate courses of action are calculated. Then orders and instructions are flowing down the chain of command to individual effector systems, in our case the anti-aircraft artillery (AAA) platform. This approach is tried and tested but also raises several issues:

a) *Network centricity:* The process heavily relies on transmitting data through the network to and from C2 nodes, which largely coordinate individual platforms, unless they operate in self-defense mode. What if communication is distrupted and bandwidth is limited? Are there other ways to reorganize local entities for effective cooperation if communication breaks down?

b) *Sensor to effector latency:* Propagating information through networks that require C2 nodes for data fusion generates sensor-to-effector latencies. Latency, in turn, can put individual AD platforms at risk if incoming threats are detected too late.

c) *Single point of failure:* C2 nodes may constitute a single point of failure. If the opponent manages to detect and take out the C2 node, the whole AD network becomes ineffective or at least massively degraded.

d) *Reconfiguration:* Even if the C2 node is not affected, loss of individual sensors or effectors in the network may require a reorganization of the compound. Currently this requires replanning, which again results in latencies. Looking at attrition scenarios, we assume that the ability of some network elements to automatically regroup could substantially improve overall resilience and effectiveness.

[4] Balancing short-term reward intake with long-term objectives is part of the "temporal credit assignment problem."

[5] The actual implementation requires skillful engineering of what constitutes an "action:" The system must learn how to use radar functions in a sensible way, for example, by allowing a tracker to initialize and maintain a track with reasonable accuracy. We are currently working with macro-actions, which provide complete implementations for certain tasks. Moreover, we are experimenting with a combination of "track-before-detect" and "attention-based tracking" to analyze if these trained, model-free variants would enable faster effector engagement and better self-protection in high treat scenarios.

[6] https://www.darpa.mil/about-us/darpa-perspective-on-ai.

[7] AI classifiers typically use tutorial training. In this case, the immediate tutorial input is used to form an error signal, which is backpropagated into the classifier to adjust those parameters, which had the highest contribution to the error.

e) *Ad-hoc support:* Attackers commonly exploit the "relative strength principle." This means that attackers will try to concentrate force at a specific and narrow point of the defender to temporarily overwhelm it. Even if the defender massively steps up its efforts, it is almost impossible to avoid that forces at the point of attack quickly run out of ammunition, while the larger part of the defense infrastructure is almost unaffected. We speculate, that a system, which is able to locally reorganize, can provide ad-hoc support to the very forces under heavy attack and reinforce them quicker.

f) *Economy of effort:* Multiple systems of an IADS cover the same airspace. In practice each of these systems has its own C2 component. These C2 components need to decide or negotiate which effectors to deploy, such that economy of effort is preserved. This decision is highly context sensitive.[8] We assume that a system that properly understands this context will be able to make more effective effector choices commensurate with the threat.

To explore these hypotheses, our objective was to experiment with a setup, which does not have a C2 component at all. Rather our system is composed of individual AD platforms that learn how to cooperate and find an effective and emergent defense response against any incoming threat.[9] In essence, we strive to learn policies, which motivate other agents in the same team to cooperate. To do so, we model joint behavior amongst our AAA platforms as a Decentralized POMDP (DecPOMDP).

The general idea is to develop a "theory of mind" among agents, i.e., we assume that actions amongst agents are communicative acts. Agents can interpret a fellow agent's action when they observe them and learn which actions to take to convey a maximum of information to others [9]. As a result, agents learn when and what to communicate to each other to best achieve joint and individual goals.[10] From a technical perspective the major challenge was to extend the training procedure to explore in policy space and not – as usual – in action space, as one agent's belief about another agent's current state depends not only on the current state and observed action, but also on the policy explored.

First training results showed substantial instabilities in performance. Although training performance reached good performance levels, performance deteriorated massively when making slight changes to the agent team. Our analysis showed that agents learned "idiosyncratic"[11] behavior. After changing the training protocols to implement cross-play and league play schemes, results could be stabilized. As our preliminary results, discussed in more detail below, make clear, this also vindicated the resilience hypothesis presented above. Further investigation and training of the system is required to potentially learn optimal communication patterns and timing under low communication bandwidth constraints or electronic warfare (EW) conditions.

C. *GhostPlay's Approach to Simulation*

The in-process combat simulator is a central piece of the GhostPlay environment. The simulator orchestrates interaction among objects in a staged war gaming scenario. The simulator's computing power is key as scenarios with a fairly large number of entities need to be played quickly over several thousand time steps. Therefore, the simulator was built to be deployable "in-process" and directly interact with the objects to be trained without network latency. The simulator also has precautions to play scenarios in multiple time resolutions.

The simulator is extensible horizontally by adding new objects to the scenario and vertically by extending individual models with more details. While playing low resolution scenarios, the simulator works primarily with probabilistic models (representing summary statistics of interaction effects) and targets temporally extended scenarios as they would occur in an Anti-Access/Area Denial (A2/AD) situation. Equipped with higher resolution models, we have specified operational behavior down to level of modeling mechanical latencies of AAA turret movements or individual sensor control.

D. *Preliminary Results*

GhostPlay's preliminary results are encouraging. After less than one year of simulation-based research we observe that AD components behave in novel ways. New patterns reflect core tenants of the principles of war, as we argue below.

1) *Single Platform Tactics*

GhostPlay deliberately started out modelling a single air defense platform thereby using the FlakPz Gepard, a German AAA system, that is largely self-sustaining. The Gepard is also most qualified for the GhostPlay scenarios that require an AD system to operate on-board active sensors (search radar and tracking radar function) and passive sensors (optical periscope and infrared sensor) plus effectors while engaging targets on the move. We also wanted to experiment with different coordination policies to analyze, if platform behavior adapts commensurate with additional sensor and effector capabilities, as this would suggest that the platform was able to learn how to use additional technical capabilities. Therefore, we equipped the AAA with hypothetical additional sensor (e.g., infrared sensor) and effector capabilities in the simulation. We also wanted to know if the policies learned would take advantage of a fused Recognized Air Picture (RAP) using information from multiple sources and thus provided the system with a link-based, centrally supplied RAP.[12]

[8] Economy of effort suggests that it might not be economic to attack an artillery missile which costs US$150k with an AD missile that costs US$8m – unless the artillery missile may destroy an entity, which is an extremely important part of the defender's infrastructure. Disobeying economy of effort may quickly turn into massive losses of defensive capabilities and resilience.

[9] This is a rather radical standpoint. We expect that a real-world deployment will contain certain data aggregation and command nodes, however that individual systems will be able to work without them, but if they are available, make optimal use of them.

[10] The policy explored, which defines the behavior of agents, is assumed to be common knowledge to all agents in the team.

[11] For example, a AAA agent was observed to switch on its search radar. As the platforms have learned to operate mostly with passive sensors and networked RAPs, other agents believed this action to suggest the platform wants to signal that it is being attacked. This interpretation is not totally unintuitive. In general, however, switching on the search radar implies only that the platform wants to acquire more information about its close surrounding and does not automatically imply that the platform is under attack. If other agents do misinterpret such a behavior, they might move towards the sending platform to help, thereby giving up their position for no real reason.

[12] The RAP would be produced by a larger range data fusion process, using more powerful and longer-range sensors. As the RAP production involves processing and human validation of classification and identification, it provides a wider area view but may supper from reporting latency, to be considered when associating such information to local sensors.

This single-platform setup has produced a series of interesting findings that can be summarized as follows:

a) *The system learns sensor-control strategies to improve target classification.* Traditionally, for example, an AI classifier receives a video frame produced by the periscope camera to classify a target. In contrast, a periscope using the GhostPlay policy first learns how to zoom-in on a certain coordinate of interest as this leads to faster convergence on a stable classification.[13][14]

b) *The system learns multi-sensor control strategies:* The system is able to learn policies which implement situation-specific trade-offs between relying largely on passive sensors and deploying active sensors to minimize the risk of being detected and attacked by radiation-following missiles.[15]

c) *System learns to change behavior when a RAP is available:* In the same scenario the system behaves differently if it acts upon RAP-ensured situational awareness. Behavioral changes are most notable for the use of passive sensors (periscope). These sensors are mainly used for 360° searches if the global air picture is not available. For example, search directions focus on incidents when the platform needs the most time to turn due to mechanical constraints or to adjust the turret position early on to anticipate incoming threats.

d) *System learns to prioritize:* The system learns how to prioritize target engagements. We have used a swarm of 105 UAVs. The swarm flew in a pack formation and broke up shortly before the AD system to stage individual attacks. In the most demanding scenario 105 individual trajectories were meant to confuse the AAA sensors. At the moment the swarm broke up, a high-velocity threat approached the AAA system from a different angle. The system has mastered the challenge of, first, detecting the high velocity threat; second, recognizing that this threat is far more serious than the UAV swarm; and third, turning turret and weapon to engage this threat while the UAV swarm continues to perform fancy maneuvers.

e) *The fire-control policy learns appropriate timing.* The system learns policies, which discriminate between platforms that deploy weapons (e.g., attack helicopters or UCAVs) and loitering ammunition. Generally, the learned policy shows a tendency to engage loitering ammunition later and weapon carrying vehicles earlier if they are in reach of effectors.[16]

f) *The fire-control policy compensates low sensor resolution or track drops with UAV swarms:* Especially in attacks by smaller scale UAVs (e.g., attrition attacks) sensor systems and trackers may not be able to resolve each UAV individually or produce switching tracks and/or lose/drop tracks required to re-initialize. We observe that the learned fire control policy is comparably robust to these issues. The policy learns to engage a "pulk" with a series of coordinated barrage fire patterns to gradually reduce the swarm size, even when tracks have a comparably wide covariance. Should further tests vindicate this behavior, sensor quality would matter less to AAA systems, while opportunities to operate these systems with remote sensors (e.g., using sensors from other platforms or forward deployed sensors) would significantly increase.

Overall, we trained the AAA platform against a variety of different threats, ranging from single UAV/UCAV like the Bayraktar TB2, drone swarms, and helicopter attacks represented by Ka-52 and Mil Mi-28 combined with fast approaching missiles. Attackers were modeled with "local rule-based intelligence,", i.e., the attack pattern and objective were predefined with pre-specified approach trajectories. Attackers, however, operated on modeled rulesets prescribing how to respond to the detection of and the engagement by an AD system.[17] All models had associated a probabilistic damage model, which allowed realistic effector impact estimation on a target object, given the target's physical structure, effector type and impact area.

Preliminary results suggest that the AAA platform learns very fine-granular engagement tactics for different types of threats and even senses when it is important to destroy the target or only disable it. Compared to a traditional OODA workflow implementation, our system reduces the volume of ammunition required to protect assigned objects by around 12% vis-à-vis helicopters and up to 42% in scenarios against attacking swarms.[18] The project will extend and verify these figures further to publish detailed reports in the project's mid-term report. We plan to open the simulation environment and/or to establish a test bed, where vendors can compare their individual control strategies.

2) Multi-Platform Tactics

In addition to single-platform scenarios, we combined multiple AAA units of the same type to protect an airfield as a a scenario-specific high value asset (HVA). The intention of these training runs was to get first insights in what could be expected from having multiple AAA systems learning to team

[13] Similar to DeepMinds AlphaStar the action space is implemented with action macros, i.e., the system first determines the type of action (e.g. sensor control, effector-control, sensor number, all subsequent fields are then interpreted in context of the action macro).

[14] An interesting new opportunity is to connect the FlakPz with a passive sensor network (like TwinVis), with the passive system acting as a preliminary guidance and pre-warning system. Preliminary evidence suggests that this combination could greatly strengthen the survivability of the FlakPz as it reduces its electromagnetic emission.

[15] Evidence from some scenarios suggests that policies have learned to use the tracking radar to provoke the target to change direction in the attempt to escape the tracking beam. However, this needs to be analyzed in more detail, especially to ensure that observed behavior is stable and not just an unwanted artefact. This analysis will be done in the second project phase, where we plan to use a more elaborate aerial vehicle behavior in contrast to the current rules-based approach.

[16] As of now this is just an observation. We have not yet properly analyzed this behavior. But looking at scenario runs with platforms that carry weapons and use earlier generations of the trained policy suggests, that the earlier engagement may preempt the release of weapons by the platform. "As-early-as-possible" engagements also occur in scenarios with platforms that use models of laser-guided weapons, which could be interpreted as further evidence underpinning the observation.

[17] Following the principles discussed in [7] the local behavior in response to imminent threats and the orchestration of attacks while being engaged by the AD systems were modelled by Fuzzy inference but adapted for SEAD missions.

[18] In several UAV swarm scenarios, excess ammunition required by the OODA workflow-controlled systems was not the main issue. In these cases, the AAA platform simply did not survive the scenario.

up freely and without a central C2 coordination. We have achieved the following preliminary results:

a) *A group of AAA platforms learned to cooperate in defending against a drone swarm with 30 UAVs:* The AAA platforms' cooperative tactics was already rather complex (FIGURE 2): AAA platform 1 used its active sensors, while platforms 2 and 3 were observing the situation under emission control (EmCon). As 10 UAVs separated from the swarm to engage AAA platform 1, 20 UAVs proceeded further to the airfield as the main target. While AAA 1 engaged the attacking UAV swarm, AAA 2 attempted to sneak in by the main swarm. Meanwhile AAA 3 pretended being a "lame duck." Shortly before the UAV swarm staged its attack AAA 2 and 3 simultaneously engaged the main swarm. It turned out that the move of AAA 2 created a situation that severely restricted the freedom of maneuver of the swarm, which could be effectively neutralized. In 30% of all scenarios in which the AD systems had not been using this policy, the swarm prevailed and damaged the airfield significantly. By contrast, the AAA team using this policy outperformed the swarm in 98% of all scenarios played and protected the airfield.

FIGURE 2: AAA PLATFORMS (BLUE) DEFEND AIRFIELD AGAINST AGGRESSOR SWARM (RED). VIDEO MATERIAL GHOSTPLAY.

b) *Increasing survivability by re-organization:* In further tests we STARTED to investigate the effects of attrition attacks. We used 10 AAA systems to protect a HVA against an aggressor swarm of 105 UAV. The 10 AAA systems were positioned around the HVA. The attacking swarm leveraged the principle of "relative strength," which means that 70-90 UAVs would concentrate on a geographically small area, creating an overwhelming force for the two or three AAA systems deployed in that region. In parallel smaller UAV swarms would try to distract AAA systems and keep them busy in their positions. The concentrated force led to unavoidable losses of AAA systems in the scenario. In earlier training stages the AAA solution was lost and the number of UAVs that survived was large enough to attack the HVA. At later stages of the policy, the AAA platforms learned to continuously re-organize group assignments and re-prioritize targets. Consequently, whenever one AAA system was becoming dysfunctional another AAA platform was moving in (even preemptively, when a AAA platform was running low on ammunition), such that the UAV swarm was substantially decimated and no longer able to substantially harm to the HVA. Overall, the policy suggests that in 9,864 out of 10,000 scenarios a constellation of 10 AAA was able to put up effective protection against a 105-member UAV swarm, losing not more that 3 AAA platforms.

We need to emphasize that these are early preliminary results based on idealized assumptions. For example, the scenarios assume that AAA platforms share internal status information among them and can freely choose sensor deployment without having to adhere to EmCon rules. In addition, the AAA platforms did not have any restrictions to move out of their positions, nor were they bound by rules of engagement (RoE). We will use further simulation runs to explore how different RoE will affect the freedom of maneuver of the AAA platforms under consideration. We will also scrutinize how RoE need to be crafted to ensure effective human control, without preventing the AAA platforms from delivering the results already accomplished.

In addition, there are several technical caveats. On the one hand it is by no means certain, that operating multiple AAA platforms in a federation without central coordination[19] would produce any meaningful results. On the other hand, all AAA platforms could just jump on the same target as soon as it is in reach of their effectors, thus using available capacities very inefficiently. Although our preliminary results are very encouraging, we have taken precautions to learn stable policies thereby using team rotations, "other-play" and learning protocols like league-updates. Further research is needed to ensure, that policies do not learn to agree on implicit communicative acts, which would break the POMDP conditions and may lead to instable behavior. Given imperfect perception models and simulated "fog-of-war" effects, the latter may be substantially more difficult as compared to computer games and will require further efforts in upcoming project phases.

3) *Summary*

Initial findings suggest that learned policies can create behavioral patterns that reflect key principles of war. More fine-granular control of the sensor-effector network reduces the amount of force required (economy of force) to establish effective protection (objective). Our AAA systems advance situational awareness at the platform level by considering more information than only kinematic aspects of the target object. This enables the platform to anticipate adversarial moves and enables emergent and adaptive countermeasures. This behavior will make it impossible for the adversary to "read" and understand the AAA system. Thus, air defenders can exploit newfound elements of surprise that shift the initiative to their benefit.

Defense systems leveraging network-centric warfare mainly focus on building federated solutions by seamlessly integrating all components. Our preliminary results show that cognition is about to significantly augment these federations as every component can interpret the current and future behavior of its companions based on policies known by all elements of the federation. This would offer new ways to ensure resilience in non-benign environments in which communication is likely to be missing and data will be corrupted.

[19] In practical deployments there is at least an assigned sector of responsibility in which the platform actively engages targets.

III. Balancing Ethics with Performance

In democracies armed forces operate within a framework set by ethical and moral principles as well as the rule of law.20 Within this framework, armed forces will sooner, rather than later, grapple with technical autonomy. In this context, defense AI causes significant concerns as it serves the use of force. Therefore, if defense AI is used to defend democracies, it must necessarily be embedded in national legal and value-oriented frameworks, relevant supranational rules and international law. In practice, however, it proves to be a major challenge to incorporate legal, ethical, or societal norms into the functions of AI systems.

Since 2017, governmental and non-governmental organizations have produced lists that outline generic, mandatory quality attributes for AI systems. These lists can be seen as a first attempt to combine ethical, legal, societal, and technological considerations. But these lists are far from sufficient to realize or promote core values such as human dignity and freedom, peace and justice, or soldierly virtues such as love of one's homeland, truthfulness, or courage.

Thus, a key research aspect of GhostPlay is to evaluate the applicability of the new IEEE 7000™ 2021 standard for Value-Based Engineering (VBE), which became effective in September 2021. Ideally, applying this standard would lead to defense solutions, with different qualities. That's why GhostPlay wants to consider the entire universe of values that German Armed Forces attribute to their leadership principle of Innere Führung. Being in close contact and contributing to the standard's further evolution, GhostPlay will be the first defense AI application worldwide designed to fully comply with IEEE 7000™-2021.

Moreover, GhostPlay's use of the IEEE 7000TM standard will produce learning materials to train Value Leads, a new job description in systems development. These Value Leads possess the philosophical and technical understanding required for VBE with the goal to make Germany a pioneer and leading nation educating value-sensitive defense AI engineers and developers.

IV. GhostPlay's Approach to Innovation Management

GhostPlay is a capability and technology development project that uses cutting-edge insights from academic as well as applied research to provide the Bundeswehr with a novel level of tactical versatility. Tactical versatility complements the Bundeswehr's strive for information, decision, and effects superiority. GhostPlay's key added value stems from the fact that context and consequence-aware solutions can be transferred across applications used in different military domains. This creates valuable opportunities for cross-pollination between domains and military services.

Ultimately, GhostPlay's demanding development agenda requires an innovation management approach that is agile and holistic. To this purpose GhostPlay combines the Real-Option approach [8] with an agile development process. With this approach new research and implementation topics are assessed according to their expected operational value, adopting a hypothetical pricing scheme, like financial option pricing. As the scheme takes into account internal and external risk factors, it balances risks and opportunities to maximize the expected operational value, which can be created by the assigned budget.

Practically, the innovation portfolio is evaluated every six months, combining external information about recent conflicts, technology trends and recent initiatives of Western forces, collected and organized by the Defense AI Observatory, with actual market requirements as perceived by industry partners and the proper findings of our research project.

V. Outlook

After one year, GhostPlay has delivered encouraging results that underline the feasibility and potential improvements of tactical AI and emergent coordination in an AD environment.

Already at this stage, GhostPlay's project partner Hensoldt has decided to transfer the project's sensor resource management capabilities into a new environment to coordinate the deployment of active and passive sensors with tactical AI. This will create new capabilities for armed forces and vindicates the project's methodological and technological approach.

Moreover, we will extend the set of principles used for GhostPlay by replacing a fuzzy logic-based interference mode currently used for attacking systems. At the next stage attackers shall use the same tactical AI and emergence principles to develop new and change existing tactics during a mission in a "counter-play" training protocol. This means that AD systems and SEAD systems would be trained in alternating cycles. Whenever a more successful AD policy is found, SEAD polices will be adapted to overcome the new AD policy and vice-versa. These "opponent-play" cycles will enable both sides to continuously learn increasingly fine granular and complex behavior, enabling them to cope with today's most dangerous threats at a certain stage.

AI-based SEAD tactics are of specific interest, as they directly address a current capability gap. To develop SEAD tactics against sophisticated threats such as S400 and S500 AD compounds, the existing AD capability will be complemented with surface-to-air-missile models, which may extend the purely reactive RL architectures used today with planning in large scale POMDP methods.

While many aspects of GhostPlay still require further research and analysis in terms of robustness and effects before they could enter operational service, the project creates added value for different military tasks:

a) *Non-traditional red teaming for future force planning:* The GhostPlay simulator and AI models can be used to test new sensor/effector constellations. GhostPlay provides the first environment, in which AI methods learn how to best use available physical capabilities. This provides force planners with advanced insights on how new sensors, effectors, communication, and platform capabilities would affect future tactics. The system can thus be used to find the best capability combinations and efficiently develop operational requirements for new systems.

[20] As industry is actively researching aspects of technical autonomy, for example, to support autonomous driving and robot assistance, there is no plausible reason, why these technologies would not show up in a military context. Thus, the effects and possibilities of such capabilities must be understood and analyzed both, in terms of future force planning and in terms of potential future threats.

b) *Non-traditional red-teaming for projects currently under development:* GhostPlay can provide a testbed for system vendors to test their concepts and tactics against a hard-to-predict adversary. Currently new systems are evaluated against scenarios and vignettes developed by military analysts, but the selection of scenarios is biased towards allied doctrine and allied thinking on expected adversarial behavior. By contrast, GhostPlay operates "model-free" and learns tactical behavior without any preselected vignettes. This approach provides behavioral patterns not yet seen in practice or in existing models and thus augments existing testbeds, better prepare allied systems, and potentially uncovers unknown weaknesses in systems under development.
c) *Non-traditional red-teaming for crew-training:* Being setup in a DIS (IEEE) framework, GhostPlay components can be integrated in pilot and air defense simulators to train crews on yet unseen tactics.
d) *Transferring GhostPlay to other domains and mission areas:* GhostPlay's approach and policies can underpin the development of defense solutions meant to coordinate complex intercept missions without a central C2 component. This could provide novel solutions to protect naval platforms against surface and subsea threats and could enhance solutions to provide Joint Tactical Fire Support (JTFS), for example.

Finally, GhostPlay partners also mull the idea of potentially operating a "GhostPlay light" environment, i.e., a digital twin of the simulation environment with lower fidelity and unspecific sensor models. "GhostPlay light" could be hooked up with commercial video games. The intention is to leverage the "wisdom of the crowd" by involving many professional, semi-professional and hobby pilots to detect new and unconventional tactics. These new tactics could then be used to confront and refine GhostPlay. The respective results could be transferred into the restricted simulation environment of armed forces, which operate realistic sensor models.

Acknolodgement

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [GhostPlay].

Literature

[1] Work, Robert O. and Shawn Brimley, 20YY. Preparing for War in the Robotic Age, Washington, DC, Center for a New American Security, 2014.

[2] Science and Technology Trends 2020-2040. Exploring the S&T Edge, Brussels, NATO Science and Technology Organization, 2019.

[3] Horowitz, Michael C. and Shira Pindyck, "What is a military innovation and why it matters," Journal of Strategic Studies, 2022, https://doi.org/10.1080/01402390.2022.2038572 [Last access 31 August 2022].

[4] Borchert, Heiko, Torben Schütz, Joseph Verbovszky, Beware the Hype. What Military Conflicts in Ukraine, Syria, Libya, and Nagorno-Karabakh (Don't) Tell Us About the Future of War, Hamburg, Defense AI Observatory, 2021, https://defenseai.eu/daio_beware_the_hype [Last access 31 August 2022].

[5] UK Defence Doctrine, Joint Doctrine Publication 0-01, Shrivenham, Development, Concepts and Doctrine Center, 2014.

[6] Ernest, Carroll, Lee, et.al, Genetic Fuzzy based Artificial Intelligence for Unmanned Combat Aerial Vehicle Control in Simulated Air Combat Missions. DOI:10.4172/2167-0374.1000144 [Last access 31 August 2022].

[7] İşci, Hasan, Gülay Öke Günel, Fuzzy logic based air-to-air combat algorithm for unmanned air vehicles, International Journal of Dynamics and Control, 10:1 (February 2022), https://link.springer.com/article/10.1007/s40435-021-00803-6 [Last access 31 August 2022].

[8] Trigeorgis, Lenos, Real Options. Managerial Flexibility and Strategy in Resource Allocation, Cambridge, MIT Press, Cambridge, 1999.

[9] Foerster, Jakob N. et. al., Learning to Communicate with Deep Multi-Agent Reinforcement Learning, archiveX, https://arxiv.org/abs/1605.06676 [Last access 31 August 2022].

[10] Uppal, Rajesh, "Israel successfully tests multilayered air defense system to defend against barrage of short-, medium-, and long-range ballistic missiles," IDST, 15 May 2022, https://idstch.com/geopolitics/srael-successfully-tests-multilayered-air-defense-system-to-defend-against-barrage-of-short-medium-and-long-range-ballistic-missiles/ [Last access: 31 August 2022]

[11] Sun, Yi, Daan Wiestra, Tom Schaul, and Jürgen Schmidhuber, "Stochastic search using the natural gradient," ICML 09: Proceedings of the 26th Annual International Conference on Machine Learning, 2009, https://dl.acm.org/doi/10.1145/1553374.1553522 [Last access: 31 August 2022]

[12] Wiestra, Daan, Tom Schaul, Tobias Glasmachers, Yi Sun, Jan Peters, Jürgen Schmidhuber, "Natural Evolution Strategies," Journal of Machine Learning, 2014, https://jmlr.org/papers/v15/wierstra14a.html [Last access: 31 August 2022]

[13] Graves Alex. et.al., "Hybrid computing using a neural network with dynamic external memory,", Nature, 20 October 2016, https://www.nature.com/articles/nature20101 [Last access: 31 August 2022].

[14] Kanerva, Pentti, Sparse Distributed Memory, Boston, MIT Press, 1988.

Neue Produktionsstrukturen für die Flugzeugfertigung der Zukunft

Alexander Wenzel*,
Peter Nyhuis
Institut für Fabrikanlagen und Logistik
Leibniz Universität Hannover,
Deutschland
*wenzel@ifa.uni-hannover.de

Hamied Nabizada, Lasse Beers,
Alexander Fay
Professur für Automatisierungstechnik
Helmut-Schmidt-Universität /
Universität der Bundeswehr

Martin Röhrig
Airbus Operations GmbH
Hamburg, Deutschland

***Kurzfassung* – Die Auftragsabwicklung im Flugzeugbau ist aufgrund stetig steigender Kundenanforderungen und der resultierenden Variantenvielfalt durch eine zunehmende technische und organisatorische Komplexität geprägt. Bisherige, auf starre Taktung ausgerichtete Produktionsprinzipien und -strukturen werden den Anforderungen an eine hohe logistische Leistungsfähigkeit bei zunehmendem Kostendruck nicht mehr gerecht. Es bedarf daher neuer Ansätze zur Gestaltung, Planung und Steuerung der Produktionsstrukturen, die flexible und gleichzeitig effiziente Abläufe ermöglichen. Insbesondere vor dem Hintergrund zunehmender Entwicklungsarbeiten zur Automatisierung bestimmter Teilprozesse bei der Flugzeugherstellung bietet die Erweiterung herkömmlicher Organisationsformen zu hybriden Produktionsprinzipien, in denen beispielsweise Montagelinien um modulare Produktionsbereiche ergänzt werden, das Potenzial, eine höhere logistische Leistungsfähigkeit bei gleichzeitig hoher Variantenvielfalt zu erreichen. In diesem Beitrag werden wesentliche Potenziale, Herausforderungen sowie grundlegende Ansätze zur Realisierung hybrider Produktionsprinzipien vorgestellt.**

Stichworte – Hybride Produktionsprinzipien, Produktionssystemgestaltung, Model Based Systems Engineering, Produktionsplanung und -steuerung

I. Einleitung

Über 10.000 Flugzeuge der A320-Familie sind in den vergangenen vier Jahrzehnten ausgeliefert worden. Die Entwickler gingen damals optimistisch von ein paar hundert Flugzeugen aus. Somit lag der Schwerpunkt im Design auf der Produktperformance; die heutigen Produktionsraten waren damals unvorstellbar. Die über die Jahre gestiegene Produktionsmenge, -vielfalt und -komplexität stellt somit die bisherige Produktion vor große Herausforderungen. Ein wesentliches Ziel des Herstellers ist eine signifikante Beschleunigung des Flugzeugentwicklungsprozesses und damit die Möglichkeit, mit schnelleren Produktzyklen die sich wandelnden Marktanforderungen schneller zu befriedigen. Die Digitalisierung der Entwicklungsprozesse und die frühe und effiziente Einbindung planerischer Aktivitäten rund um die Produktionssystemgestaltung zur Herstellung des neuen Flugzeuges sind hierfür erforderlich [1].

Daraus ergibt sich, dass die Produktionsgestaltung, ausgelegt für die eben beschriebenen Anforderungen, frühzeitig die Gestaltung des Produktes beeinflusst. Zentraler Punkt ist dabei die Kundenvarianz. Der Kundenentkopplungspunkt sollte so spät wie möglich gewählt werden, um so eine möglichst hohe externe Varianz bei gleichzeitig geringem Einfluss auf die Produktionsabläufe zu ermöglichen. Dieses wiederum erlaubt einen hohen Grad an effizienter Automatisierung in den frühen, kundenneutralen Produktionsprozessen, wie beispielsweise in der Fertigung der Rumpfstruktur. Um dies zu erreichen, werden neue, flexiblere Produktionsstrukturen benötigt, die diesen Anforderungen der hochkomplexen Klein-Serienfertigung gerecht werden. Um derartige Strukturen in der Flugzeugfertigung zu implementieren, bedarf es einer Planungssystematik, die ein Vorgehen definiert, wie mittels des Co-Designansatzes Produkt- und Produktionsstrukturgestaltung in Einklang gebracht werden können, um eine optimale Lösung für Produktstruktur und Produktionsstruktur zu realisieren. Das Model Based Systems Engineering (MBSE) ist eine Möglichkeit zur methodischen Beschreibung von Produktion und Produktionssystem. Mittels der logischen Beschreibung und Verknüpfung von Abhängigkeiten und Anforderungen einer hybriden Produktionsstruktur können die teilweise divergierenden Zielgrößen der Logistikleistung und Logistikkosten aufeinander abgestimmt werden.

Ziel dieses Beitrages ist es, ein Verständnis für hybride Produktionsstrukturen und die damit verbundenen Abhängigkeiten und Herausforderungen des Co-Designs im Flugzeugbau zu schaffen. Zusätzlich soll durch das Aufzeigen drei grundlegender Forschungsschwerpunkte die Grundlage für die Entwicklung eines ganzheitlichen Ansatzes zur zukünftigen Produktionssystemgestaltung im Flugzeugbau geschaffen werden.

Der Beitrag ist wie folgt strukturiert: Im zweiten Abschnitt wird der aktuelle Stand der Forschung dargelegt und das Themenfeld hybrider Produktionsstrukturen eingeführt. Im dritten Abschnitt werden die mit der Hybridisierung von Produktionsstrukturen einhergehenden Potentiale sowie zu lösende Herausforderungen herausgearbeitet. Der vierte Abschnitt stellt drei wesentliche Forschungsschwerpunkte vor, die zur Lösung der identifizierten Herausforderungen beitragen sollen. Im fünften Abschnitt wird dieser Beitrag mit einer Zusammenfassung und einem Ausblick abgeschlossen.

II. Stand der Forschung

Viele Anstrengungen zur Beherrschung der Variantenvielfalt innerhalb von Fließlinien, zum Beispiel durch die vertikale Trennung von variantenneutralen und

https://doi.org/10.24405/14551

variantenspezifischen Produktkomponenten [2] oder durch die Vermeidung von Modell-Mix-Verlusten durch gezielte Reihenfolgeplanungen [3], stoßen bei hochkomplexen Produkten wie Flugzeugen an ihre Grenzen. Dies liegt insbesondere daran, dass die sinkende Anzahl an standardisierten, variantenneutralen Komponenten die eigentlichen Vorteile der Linienfertigung schmälert [4]. Zur langfristigen und effizienten Beherrschung der zunehmenden Variantenvielfalt sehen neue – bislang primär durch die Automobilindustrie initiierte und noch kaum wissenschaftlich untersuchte – Ansätze die Abkehr von der reinen Linienmontage hin zu hybriden Organisationsstrukturen vor [5]. Dabei lässt sich der Grundgedanke dieser Ansätze wie folgt zusammenfassen: Durch die Entwicklung neuer Organisationsformen wird das über das Paradigma der *Lean Production* etablierte, klassische Prinzip der reinen Fließfertigung zugunsten einer eher taktzeitungebundenen (werkstattorientierten) Fertigung aufgelöst oder in geeigneter Form zu hybriden Strukturen erweitert. Der Grad zwischen einer vollständigen Auflösung und einer individuellen Erweiterung der Linienfertigung zum Beispiel durch modulare Bypässe ist dabei von einer Vielzahl an produkt- oder prozessrelevanten Randbedingungen abhängig. Basierend auf der Arbeit von FRIES ET AL. lassen sich Bypässe hinsichtlich ihrer Eigenschaften in drei wesentliche Klassen einordnen [6]:

- Ortsabhängig
- Ortsunabhängig
- Ortsunabhängig und kompetenzverändernd

ABBILDUNG 1 verdeutlicht die unterschiedlichen Eigenschaften und stellt diese anhand eines fiktiv gewählten Beispiels, basierend auf einer zentralen Fließlinie, auf der zwei Varianten montiert werden, dar.

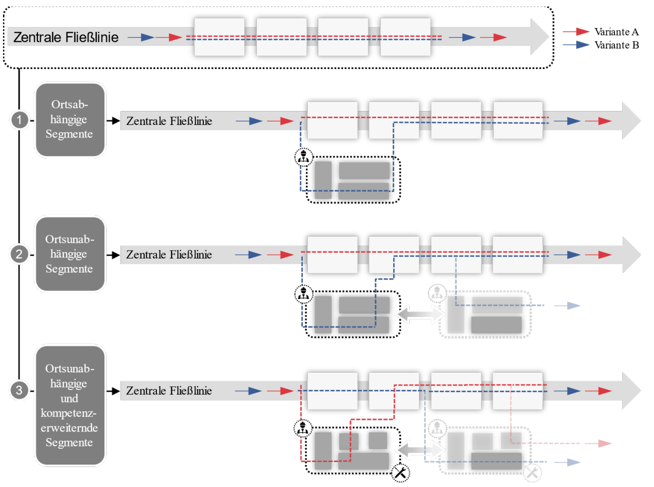


ABBILDUNG 1: POTENZIELLE ORGANISATION HYBRIDER PRODUKTIONSSTRUKTUREN.

Im oberen Teil der Abbildung ist eine zentrale Fließlinie, auf der zwei Varianten montiert werden, dargestellt. Diese wird exemplarisch um die oben erwähnten Klassen von Bypässen erweitert. Zunächst wird die zentrale Fließlinie durch ein ortsabhängiges Segment erweitert, auf dem Teile von Variante B gefertigt werden können, was neue Freiheitsgrade in der kurzfristigen Auftragssteuerung schafft (1). Dieses Segment ist in (2) durch eine ortsveränderliche Arbeitsstation ersetzt, die eine dynamische Anpassung des Layouts erfordert, aber damit auch zusätzliche Flexibilität ermöglicht. Im unteren Teil der Abbildung ist eine Kombination eines ortsunabhängigen und kompetenzerweiternden Segments dargestellt, die weitere Freiheitsgrade sowohl bei der kurz- als auch langfristig ausgelegten Gestaltung und Strukturierung der Produktion eröffnet (3).

Göppert et al. beschreiben einen Ansatz zur frei verketteten Montage. In diesem Ansatz werden räumliche und zeitlich starre Verkettungen der einzelnen Montageressourcen vollständig aufgelöst und somit eine individuelle und flexible Montageabfolge für jeden Auftrag ermöglicht. Eine Auftragsroute wird dabei auftragsindividuell festgelegt, sodass für mehrere Aufträge eines Produkttyps in Abhängigkeit der vorhandenen Montageressourcen unterschiedliche Auftragsrouten resultieren können. Dies erleichtert es, für unterschiedliche Varianten unterschiedliche Ressourcen anzusteuern, bei belegten Ressourcen auf Alternativen auszuweichen und ohne Berücksichtigung der räumlichen Reihenfolgerestriktionen weitere Montageressourcen zu integrieren. Um dieses Potenzial nutzen zu können, erfordert es jedoch die Möglichkeit, Aufträge zwischen einzelnen Bearbeitungsschritten kurzfristig zu puffern und die Reihenfolge von Montageschritten anpassen zu können. Hieraus können unter anderem erhöhte Umlaufbestände und schwankende Durchlaufzeiten resultieren. Zusätzlich erhöht sich durch die dynamischen Auftragsrouten die Komplexität der Materialbereitstellung aufgrund von Änderungen von Bereitstellungsort, -zeitpunkt und -sequenz [7].

Einen ähnlichen Ansatz erarbeiten HÜTTEMANN ET AL., die mit ihrer Arbeit ein linienloses mobiles Montagesystem entwickeln [8]. Dabei weisen diese Konzepte der frei verketteten oder linienlosen Montage durch die vollständige Abkehr von linienbasierten Montagestrukturen deutliche Parallelen zu den Prinzipien einer Werkstattfertigung auf [9].

Im Gegensatz dazu stehen – unter dem Oberbegriff der hybriden Produktionsprinzipien zusammengefasst – Ansätze wie die modulare oder fluide Montage [6, 10], die Boxenmontage [11] oder die Matrixmontage [12], die nicht zwangsläufig die vollständige Auflösung der linienbasierten Montagestrukturen anstreben. Nach KAMPKER ET AL. handelt es sich bei diesen hybriden Montageprinzipien um einen Ansatz, der die Montage variantenunabhängiger Produktmodule in der Linie und variantenspezifische Montagevorgänge, die die wesentlichen Treiber der Komplexitätskosten darstellen, in entkoppelten Montagesegmenten oder -inseln ermöglicht [5]. Dabei lässt sich festhalten, dass mit einer steigenden Anzahl an eingesetzten modularen Montagesegmenten die Unterschiede zu den frei verketteten und linienlosen Ansätzen im Hinblick auf die Organisationsform zunehmend geringer werden.

Die Organisation der entkoppelten Segmente kann zum Beispiel nach dem Werkstatt-, Baustellen- oder nach dem Matrixprinzip gestaltet sein, wodurch ein hybrides Montagesystem aus der Verzahnung verschiedener Produktionsprinzipien entsteht. Die einzelnen Bereiche bilden dabei eine Art Bypass zur Versorgung oder - im Falle kompetenzveränderlicher Montagesegmente - eine Erweiterung der zentralen Montagelinie [6]. Dabei können die eingesetzten Montagesegmente stationär oder modular bzw. ortsunabhängig agieren, sodass eine starre Verkettung zwischen einzelnen Arbeitsstationen in der Linie aufgelöst werden kann. Eine losere Taktbindung eröffnet sowohl montageintern als auch für die montageversorgenden Prozesse Freiheitsgrade. So können zum Beispiel kürzere Taktungen durch das Ausphasen größerer Arbeitsinhalte erreicht werden. Dies ermöglicht einerseits die Montage von Produktvarianten mit grundsätzlich verschiedenem Produktaufbau in einer hochvariablen Montagestruktur und birgt andererseits das Potenzial, taktzeitspreizungsbedingte Effizienzverluste zwischen niedrig- und vollausgestatteten Varianten zu reduzieren [6, 12]. Dies führt zu verringerten Modell-Mix-Verlusten in der verbleibenden Linienmontage und zu einer Erhöhung der Variantenflexibilität durch die Teilmontage außerhalb des Bandtakts. Die für die Umsetzung der hybriden Montagestrukturen zu implementierenden modularen Montagebereiche versuchen jedoch sowohl zusätzliche Investitionsaufwände als auch einen zunehmenden Flächenbedarf. Zusätzlich steigert der zum Teil entstehende ungerichtete Materialfluss die Komplexität der Montageabläufe erheblich und erhöht somit den Planungs- und Steuerungsaufwand, zum Beispiel im Hinblick auf die Materialversorgung [11]. Dies führt dazu, dass die Prozesse für Menschen zunehmend undurchsichtiger werden.

Eine zentrale Gemeinsamkeit der identifizierten Ansätze bildet der Einsatz von Automated Guided Vehicles (AGVs). Diese übernehmen den flexiblen Transport zum Beispiel von Montageobjekten oder notwendigen Betriebsmitteln innerhalb oder zwischen einzelnen Bypässen und ermöglichen somit eine Abkehr von der oder effiziente Erweiterung der reinen Linienorganisation [13]. Die Einbindung solcher Systeme, mit einer verbundenen effizienten Steuerungslogik, sind ein wesentlicher Erfolgsfaktor dieser hybriden Produktionsprinzipien.

III. Hybride Strukturen in der Flugzeugfertigung

In diesem Abschnitt werden zunächst die Potentiale hybrider Strukturen in der Flugzeugfertigung aufgezeigt. Im Anschluss werden die damit einhergehenden Herausforderungen diskutiert.

A. Potentiale

Basierend auf dem vorherigen Abschnitt lassen sich innerhalb der identifizierten Ansätze drei wesentliche Erfolgsfaktoren identifizieren, die zu Flexibilisierungspotenzialen variantenreicher Produktion, wie es in der Flugzeugproduktion der Fall ist, führen. Diese ergeben sich im Wesentlichen aus dem Zusammenspiel von ortsunabhängigen Montagesegmenten und durch AGV betriebenen Transportprozessen. Basierend auf [8] und [10] sind die Potenziale hybrider Produktionsprinzipien inklusive einer Kurzbeschreibung in Tabelle I aufgelistet.

Tabelle I: Potenziale hybrider Produktionsprinzipien (basierend auf [8, 10]).

Nr.	*Potenzial*	*Kurzbeschreibung*
1	Intelligente und flexible Zuordnung von Aufträgen auf Montagestationen	Die aktuellen Verfügbarkeiten möglicher Montagebereiche für die jeweils zu betrachtende Variante werden mittels entsprechender Kommunikations-technologien in Echtzeit geprüft. Der Folgebereich mit der beispielsweise geringsten Wartezeit wird mit einem freien AGV angefahren.
2	Variantenabhängige Montage- und Taktzeiten	Jeder variantenspezifische Montageauftrag kann entsprechend seiner Montagezeit in einem Montagebereich verweilen. Das bedeutet, dass die Taktzeiten variabel sind und Schwankungen in der Bearbeitungszeit abgefedert werden können.
3	Reaktion auf Störungen	Durch die zum Teil fehlende starre Verkettung einzelner Montagebereiche sind die Auswirkungen von kurzfristigen oder variantenspezifischen Störungen in anderen Montagebereichen begrenzt und können z.B. durch das Hinzuziehen weiterer Montagebereiche kompensiert werden.

B. Herausforderungen

Grundlegend ist die industrielle Anwendung von flexiblen Montagestrukturen in der Flugzeugfertigung eng an technische und betriebliche beziehungsweise organisatorische Herausforderungen geknüpft, die sowohl Unternehmensprozesse als auch Ressourcen betreffen, die unmittelbar mit der Montage oder aber auch mit den begleitenden IT-Systemen verbunden sind [8]. Die Herausforderungen bei der Realisierung beziehungsweise Umsetzung hybrider Produktionsprinzipien im Flugzeugbau ergeben sich dabei aus drei wesentlichen Problemfeldern:

Das **erste Problemfeld** ergibt sich maßgeblich aus der praxisgetriebenen Entwicklung des Ansatzes seitens der Automobilindustrie. Zwar sind in der wissenschaftlichen Literatur bereits Ansätze, wie beispielsweise die Boxenmontage [11], beschrieben, deren Grundstruktur dem Ansatz hybrider Produktionsprinzipien sehr nahe kommt, jedoch fehlt bislang ein grundlegendes Verständnis des logistischen Systemverhaltens solcher hybriden Montagesysteme. Fundierte Aussagen über das Leistungsverhalten oder die Kostenentwicklung durch den Einsatz eines solchen Systems lassen sich somit bislang nicht treffen. Produktionslogistische Wirkzusammenhänge, die sich aus der Kombination flussorientierter Montagelinien und funktionsorientierter Montagesegmente (zum Beispiel nach dem Werkstattprinzip) ergeben, sind bisher nicht untersucht. Dies ist jedoch notwendig, um das logistische Systemverhalten solcher Strukturen zum Beispiel in Bezug auf Durchlaufzeitverhalten und Termineinhaltung valide bewerten zu können, um so eine zielorientierte und anforderungsgerechte Gestaltung eines hybriden Montagesystems für die Flugzeugmontage zu ermöglichen.

Das **zweite Problemfeld** bezieht sich auf die mit den hybriden Produktionsprinzipien verbundenen Bypässe und deren Eigenschaften, die zum Teil variierende Flächenbedarfe hervorrufen können. In der Flugzeugproduktion wird dieser Effekt durch die großen Bauteilabmessungen (wie zum Beispiel der Rumpfsektionen), die bereits grundlegend große Flächenbedarfe innerhalb der Montage erfordern, zusätzlich verstärkt. Im Gegensatz zu der Layoutplanung von Montagesystemen in der Automobilindustrie ist bei einem Montagelayout im Flugzeugbau zusätzlich zu berücksichtigen, dass mit zunehmendem Arbeitsfortschritt der benötigte Flächenbedarf (zum Beispiel durch das Montieren der Tragflächen) wächst und einzelne Produkte somit um Flächen konkurrieren können [14]. Durch das Produkt „Flugzeug“ ergeben sich daher bereits Grenzen der hybriden Strukturen im Hinblick auf die Modularität und somit auf die potenziell zu erzielende Flexibilität in der Flugzeugmontage. Verstärkend kommt hinzu, dass die für den Transport benötigten Fahrwege, zum Beispiel aufgrund sich verändernder Routen der AGVs, ebenfalls einen hohen Flächenbedarf aufweisen. Die klassischen Grenzen zwischen der strategischen Gestaltung einer Fabrik oder eines einzelnen Bereichs und dem operativen Betrieb verschwimmen durch die genannten Einflüsse zunehmend und stellen die Unternehmen so vor steigende Herausforderungen bei der Integration von Produktionsstrukturgestaltung und Fabrikplanung.

Das für eine effiziente Umsetzung hybrider Montagestrukturen meist unabdingbar notwendige AGV-System bildet das **dritte Problemfeld** von Herausforderungen. Der Einsatz autonom agierender AGVs ermöglicht neue Freiheitsgrade in der Montage, ist jedoch mit zunehmendem Steuerungsaufwand und steigender Komplexität in der Intralogistik zum Beispiel hinsichtlich der Materialbereitstellung verbunden. Eine hohe Komplexität hängt immer mit einer großen Menge an zu verarbeitenden Informationen zusammen. Der Einsatz neuer Informations- und Kommunikationstechnologien ist daher notwendig, um durchgängige Prozessketten für eine digital gesteuerte Großbauteilmontage zu realisieren [9]. Vor dem Hintergrund der in der Flugzeugindustrie herrschenden hohen Sicherheits- und Qualitätsanforderungen beziehen sich die technischen Herausforderungen auf die Entwicklung geeigneter adaptiver Steuerungen für mobile Ressourcen, wie zum Beispiel mobile Roboter, Regelungsstrategien für die adaptive Prozesssteuerung unter Verwendung geeigneter Messsysteme und die automatisierte adaptive Routenplanung auf Basis der AGV-Systemkonfiguration (vgl. [8]).

Zusammenfassend lässt sich festhalten, dass hybride Montagestrukturen im Flugzeugbau eine Veränderung der Aufgaben sowie des Zusammenspiels der Fabrikplanung und der Produktionsplanung und -steuerung (PPS) hervorrufen [6]. Die Planung und Gestaltung einer hybriden Flugzeugmontage wird durch die vorhandenen Wechselwirkungen zwischen den Treibern und den damit verbundenen Herausforderungen zusätzlich erschwert.

IV. Forschungsschwerpunkte

In diesem Abschnitt werden, basierend auf den zuvor herausgestellten Problemfeldern, notwendige Forschungsschwerpunkte vorgestellt, um die Flugzeugindustrie bei der zielgerichteten Gestaltung, Planung und Steuerung hybrider Produktionsstrukturen zu unterstützten.

A. Logistische Modellierung

Für eine genaue Auslegung eines hybriden Montageprinzips für die Flugzeugproduktion ist die Untersuchung des logistischen Systemverhaltens, das aus der Kombination einer Linien- und Werkstattmontage resultiert, unabdingbar. Da nicht sämtliche Konfigurationen von hybriden Montageorganisationen in der Flugzeugfertigung betrachtet werden können, müssen zunächst geeignete Grund-systemkonfigurationen erforscht werden. Diese sollten einen möglichst großen Teil der Vielfalt verschiedener Organisationsstrukturkonfigurationen sowie zukünftige Entwicklungen, zum Beispiel hinsichtlich der Automatisierungsvorhaben im Flugzeugbau, abbilden.

Die produktionslogistische Zielerreichung eines (hybriden) Produktionssystems ist maßgeblich von der Organisationsform und der Gesamtsystemkonfiguration (zum Beispiel der PPS) abhängig. Zur qualitativen Beschreibung von Wirkzusammenhängen (zum Beispiel mittels idealisierter logistischer Kennlinien oder Wirknetzen) müssen daher komplexe Wirkbeziehungen zwischen relevanten Faktoren in der Flugzeugmontage einheitlich beschrieben werden. Hierfür werden zunächst mögliche Einflussfaktoren aus dem Bereich der Montagekonfiguration im Hinblick auf die Systemgestaltung oder die Intralogistik identifiziert (zum Beispiel Variantenanzahl, Auftragszeitstreuung, Transportzeiten). Zusätzlich müssen potentielle Problemursachen und deren Wirkung auf ausgewählte, logistische Zielgrößen (zum Beispiel Durchlaufzeiten, Ausbringungsmengen) identifiziert werden. Zur Erreichung dieser Teilziele wird der Ansatz einer deduktiv-experimentellen Modellbildung verfolgt [15, 16].

Darauf aufbauend gilt es, die produktionslogistischen Wirkzusammenhänge zwischen den einzelnen Faktoren und Zielgrößen in Abhängigkeit möglicher Organisationsformen und den in der Flugzeugmontage beteiligten Kapazitätseinheiten (zum Beispiel Flächen, AGVs) mittels mathematischer Modelle zu beschreiben. Hierdurch können dann allgemeingültige Zusammenhänge so auf einen spezifischen Anwendungsfall adaptiert werden, dass eine Handlungsempfehlung für die konkrete Ausgestaltung einer hybriden Produktionsstruktur, zum Beispiel in der Rumpfmontage, abgeleitet werden kann. Abbildung 2 verdeutlicht die bisher beschriebenen Zusammenhänge anhand von zwei fiktiven Kennlinienverläufen und deren noch zu definierenden Stellgrößen „Flexibilitätsbedarf“ und „Hybridisierungsgrad“.

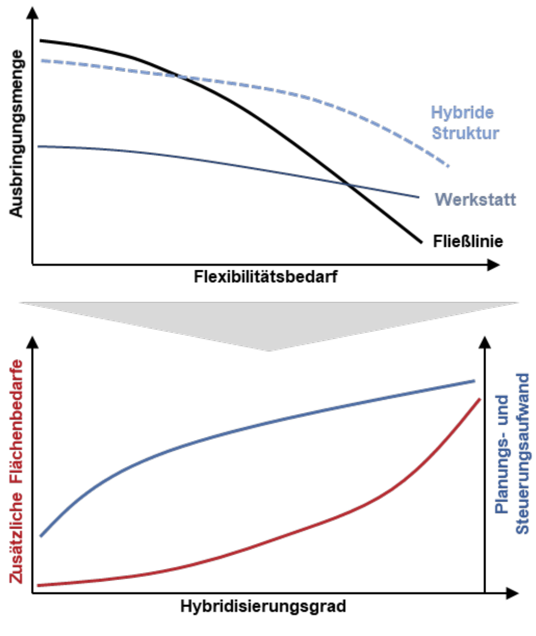


Abbildung 2: Fiktive Kennlinienverläufe für exemplarische Wirkbeziehungen zur Auslegung hybrider Produktionsstrukturen.

Zum einen kann in der frühen Planungsphase die Positionierung im Spannungsfeld zwischen dem Flexibilitätsbedarf der auszulegenden Montagesysteme und der Zielgröße „Ausbringungsmenge“ unterstützt werden. Zum anderen kann mittels der unteren, idealisierten Kennlinienverläufe eine mögliche Entscheidung hinsichtlich eines geeigneten Hybridisierungsgrades abgeleitet werden. Hierzu wurden beispielhaft die Zielgrößen „zusätzlicher

Flächenbedarf“ sowie „Planungs- und Steuerungsaufwand“ gewählt. Diese gilt es in Abhängigkeit individueller Randbedingungen des zu beplanenden Montagesystems in monetäre Faktoren zu überführen. Der Flächenbedarf ist wiederum abhängig von den gewählten Eigenschaften der modularen Bypässe (siehe Abschnitt II).

B. Planung und Steuerung der Intralogistik

Die Planung und Steuerung der Intralogistik im Flugzeugbau ist insbesondere durch die strengen Flächenrestriktionen in den Montagehallen eine herausfordernde Aufgabe. Diese strengen Flächenrestriktionen werden durch eine hybride Montagestruktur und den Einsatz von AGVs verschärft. Bislang werden im Flugzeugbau hochspezialisierte AGVs verwendet, die lediglich für eine einzelne Aufgabe ausgelegt sind. Neben dem großen Flächenbedarf weisen solche hochspezialisierten AGVs deshalb große Leerzeiten auf, was wiederum die logistische Leistungsfähigkeit der hybriden Montagestruktur schmälern würde.

Zur Reduktion der Kapitalbindungskosten und zur Erhöhung der Auslastung sollten daher AGVs verwendet werden, die nicht nur zur Erfüllung einer einzelnen Transportaufgabe ausgelegt sind und entwickelt wurden. Ein geeigneter Ansatz kann es sein, marktübliche Standard-AGVs zu verwenden, die sich bei komplexeren Transportaufgaben, wie beispielsweise dem Transport von Großbauteilen, zu einem Verbund aus mehreren AGVs zusammenschließen können, um diese Aufgabe kooperativ zu erfüllen. Weitere und dadurch neu-entstehende Herausforderungen sowie eine potentielle Herangehensweise für eine Lösung dieser Herausforderungen wurde von den Autoren des vorliegenden Beitrags bereits in [17] beschrieben. Durch die jeweilige Transportaufgabe getrieben, kann dadurch flexibel und bedarfsgerecht agiert werden.

C. Modellbasiertes Systems-Engineering

Die Systemkomplexität wächst heutzutage schneller, als sie bewältigt werden kann. Dies gilt sowohl für die Gestaltung von Produkten als auch für die Planung und Auslegung neuartiger Produktionsstrukturen. Das Resultat ist, dass herkömmliche dokumentzentrierte Methode des Engineerings nicht ausreichen, um dieser Komplexität gerecht zu werden. Daher wächst der Bedarf an modellbasierten Methoden seit Jahren weiter an [18].

MBSE wird zur Definition von Anforderungen, Systemstruktur, funktionaler Dekomposition, Datenflüssen, Software- und Hardwareverhalten und Testaktivitäten eingesetzt. Sich ergänzende Modellperspektiven definieren gemeinsam das System mit allen benötigten Informationen aus den verschiedenen Domänen. Jede Perspektive beschreibt Konventionen und Regeln für den Aufbau des Systems sowie deren Definition, um die Anforderungen der Stakeholder zu erfüllen [19]. Durch die so geschaffene Datendurchgängigkeit können Fehlerquellen, Entwicklungszeit und Intransparenz verringert und Datenqualität und Akzeptanz gesteigert werden.

Daher sollte die Darstellung jedes relevanten Sachverhalts in einer standardisierten Sprache, unter Verwendung etablierter Formalismen, ausgedrückt, gespeichert und abgefragt werden können. Denn sowohl die Rückverfolgbarkeit als auch die Reproduzierbarkeit der Ergebnisse ist abhängig von der Eindeutigkeit der Informationen und so essentiell für die Anerkennung und Verwendung der Analyseergebnisse [20].

Ein weiteres wesentliches Architekturprinzip des MBSE ist die Definition von Mustern [21]. Durch die großflächige Beschreibung einfacherer Wirkprinzipien können komplexe Systeme modelliert und analysiert werden. Abstrakte Muster sind dabei meist allgemeingütig und können wiederverwendet werden, während die spezifischen Dekompositionen dieser Muster durch anwendungsfallspezifische Daten gefüllt werden. Verschieden konfigurierte Produktionsstrukturen können so durch den MBSE-Ansatz auf den gleichen übergeordneten Mustern aufgebaut werden. Dies führt nicht nur zu einer Reduzierung des Modellierungsaufwandes, sondern gewährleistet zudem eine Vergleichbarkeit der Analyseergebnisse.

V. Zusammenfassung und Ausblick

Die Gestaltung hybrider Produktionsprinzipien für die Flugzeugmontage in Kombination mit einer hierauf ausgerichteten PPS-Konfiguration stellt ein vielversprechendes Vorgehen zur Steigerung der Flexibilität in der variantenreichen Flugzeugproduktion dar. Dennoch erhalten diese aus der Automobilindustrie getriebenen Ansätze zu hybriden Organisationsformen und die mit ihnen verbundenen Potenziale bislang kaum Einzug in weitere Industriezweige. Gründe hierfür sind zum Teil komplexe Herausforderungen, die mit einer Entwicklung und Einführung hybrider Produktionsprinzipien verbunden sind. Insbesondere das fehlende Verständnis über das logistische Systemverhalten hybrider Produktionssysteme führt dazu, dass an bestehenden Organisationsformen festgehalten wird. In diesem Beitrag wurde dargestellt, wie die Potenziale hybrider Produktionsprinzipien auf die Flugzeugindustrie übertragen werden können. Hierfür wurden Aspekte eines ganzheitlichen Ansatzes zur Integration hybrider Produktionsprinzipien in der Flugzeugmontage vorgestellt, der systematisch wesentliche Herausforderungen lösen und deren Wechselwirkungen in einem integrierten Framework, inklusive notwendiger Informationsströme und planungsrelevanter Schnittstellen, vereinen soll.

Die einzelnen Bestandteile des Frameworks, das genaue Zusammenwirken seiner Bestandteile sowie die ganzheitliche Modellierung und Analyse mit Hilfe von MBSE-Methoden sind in zukünftigen Arbeiten detailliert zu untersuchen, um eine zielführende Einführung hybrider Organisationsformen in die Flugzeugproduktion zu ermöglichen. Im Hinblick auf die logistische Modellierung muss geprüft werden, inwiefern bestehende Modelle angepasst oder erweitert werden können, um das Systemverhalten hybrider Produktionssysteme qualitativ und quantitativ beschreiben zu können.

Danksagung

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt iMOD]

Literatur

[1] A. Schirrmann and A. Zizkin, “Modellbasierter Entwurf eines Produktiossystems im Flugzeugbau,” in *Logistik in Wissenschaft und Praxis*: Springer Verlag Berlin Heidelberg, 2021, pp. 109–128.

[2] M. Röhrig, *Variantenbeherrschung mit hochflexiblen Produktionsendstufen*. Düsseldorf: VDI-Verlag, 2002.

[3] R. Koether, "Improving Productivity in Model-Mix-Assembly," in *Toward the Factory of the Future: Proceedings of the 8th International Conference on Production Research and 5th Working Conference of the Fraunhofer-Institute for Industrial Engineering (FHG-IAO) at University of Stuttgart, August 20 - 22, 1985*, H.-J. Bullinger and H. J. Warnecke, Eds., Berlin, Heidelberg, s.l.: Springer Berlin Heidelberg, 1985, pp. 761–766.

[4] J. E. Gans, *Neu-und Anpassungsplanung der Struktur von getakteten Fließproduktionssystemen für variantenreiche Serienprodukte in der Montage*: Heinz-Nixdorf-Institut, Univ. Paderborn, 2009.

[5] A. Kampker, S. Kawollek, S. Fluchs, and F. Marquardt, "Einfluss der Variantenvielfalt auf die automobile Endmontage," *ZWF - Zeitschrift für wirtschaftlichen Fabrikbetrieb*, vol. 114, 7-8, pp. 474–479, 2019.

[6] C. Fries, H.-H. Wiendahl, and P. Foith-Förster, "Planung zukünftiger Automobilproduktionen," in *ARENA2036, Entwicklung, Aufbau und Demonstration einer wandlungsfähigen (Fahrzeug-) Forschungsproduktion*, T. Bauernhansl, M. Fechter, and T. Dietz, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2020, pp. 19–43.

[7] A. Göppert, G. Hüttemann, S. Jung, D. Grunert, and R. Schmitt, "Frei verkettete Montagesysteme: Ein Ausblick," *ZWF - Zeitschrift für wirtschaftlichen Fabrikbetrieb*, vol. 113, no. 3, pp. 151–155, 2018.

[8] G. Hüttemann, A. F. Buckhorst, and R. H. Schmitt, "Modelling and Assessing Line-less Mobile Assembly Systems," *Procedia CIRP*, vol. 81, pp. 724–729, 2019.

[9] M. Bornewasser and S. Hinrichsen, Eds., *Informatorische Assistenzsysteme in der variantenreichen Montage*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2020.

[10] W. Kern, F. Rusitschka, W. Kopytynski, S. Keckl, and T. Bauernhansl, "Alternatives to assembly line production in the automotive industry," in *Proceedings of the 23rd international conference on production research (IFPR)*, 2015.

[11] K.-D. Vöhringer, "Neue Anforderungen an die Montagesystemgestaltung im Automobilbau," in *iwb Münchener Kolloquium '91*, vol. 1991, *Wettbewerbsfaktor Zeit in Produktionsunternehmen: Referate des Münchener Kolloquiums '91 Institut für Werkzeugmaschinen und Betriebswissenschaften Technische Universität München 28. Februar / 1. März 1991*, J. Milberg, Ed., Berlin, Heidelberg, s.l.: Springer Berlin Heidelberg, 1991, pp. 323–336.

[12] P. Greschke, *Matrix-Produktion: Konzept einer taktunabhängigen Fließfertigung*. Norderstedt: BoD – Books on Demand, 2016.

[13] A. Bubeck, M. Gruhler, U. Reiser, and F. Weißhardt, "Vom fahrerlosen Transportsystem zur intelligenten mobilen Automatisierungsplattform," in *SpringerLink, Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Technologien, Migration*, T. Bauernhansl, M. ten Hompel, and B. Vogel-Heuser, Eds., Wiesbaden: Springer Vieweg, 2014, pp. 221–233.

[14] H. Prinzhorn, S. Wesebaum, and G. Ullmann, "Planung zeitdynamischer Layouts für XXL-Produkte," *ZWF-Zeitschrift für wirtschaftlichen Fabrikbetrieb*, vol. 1413, no. 10, pp. 608–611, 2015.

[15] P. Nyhuis and H.-P. Wiendahl, *Fundamentals of Production Logistics: Theory, Tools and Applications,* 1st ed. Berlin, Heidelberg: Springer Verlag Berlin Heidelberg, 2009.

[16] M. Schmidt, *Modellierung logistischer Prozesse der Montage*. Garbsen: TEWISS Verlag, 2011.

[17] F. Gehlhoff *et al.,* "Challenges in Automated Commercial Aircraft Production," *IFAC-PapersOnLine*, vol. 55, no. 2, pp. 354–359, 2022.

[18] J. D'Ambrosio and G. Soremekun, "Systems engineering challenges and MBSE opportunities for automotive system design," in *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 2017.

[19] F. Demoly, D. Monticolo, B. Eynard, L. Rivest, and S. Gomes, "Multiple viewpoint modelling framework enabling integrated product–process design," *Int J Interact Des Manuf*, vol. 4, no. 4, pp. 269–280, 2010.

[20] A. M. Madni and M. Sievers, "Model-based systems engineering: Motivation, current status, and research opportunities," *Syst Eng*, vol. 21, no. 3, pp. 172–190, 2018.

[21] M. Elaasar, N. Rouquette, S. Jenkins, and S. Gerard, "The case for integrated model centric engineering," *Proceedings of the 10th model-based enterprise summit (MBE 2019). National Institute of Standards and Technology, Gaithersburg, MD*, pp. 9–16, 2019.

Entwicklung eines generischen Modells für die standardisierte Beschreibung von Ressourcen in der Luftfahrtproduktion

Lasse Beers*, Maximilian Weigand, Alexander Fay
Institut für Automatisierungstechnik
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Hamburg, Deutschland
*lasse.beers@hsu-hh.de

Alain Chahine
Airbus Operations GmbH
Hamburg, Deutschland

***Kurzfassung* – Um in frühen Phasen des Engineerings Entscheidungen über die Konfiguration von Produktionssystemen zu treffen, sind Modelle von verfügbaren Produktionsressourcen notwendig. Um diesem Bedarf gerecht zu werden, wurde ein SysML-Modell entwickelt, mit dessen Hilfe eine einheitliche Beschreibung von Komponenten, Schnittstellen und Fähigkeiten von Produktionsressourcen möglich ist. Die Granularität des Modells ist relativ grob, da zwar eine gewisse Dekomposition der Ressourcen in einzelne Komponenten möglich sein soll, jedoch keine physikalische Repräsentation vorgesehen ist. So kann es effizient und automatisiert ausgewertet werden, ohne detailreiche und rechenintensive Simulationen durchzuführen. Zukünftig soll die Kompatibilität von unterschiedlichen Ressourcen basierend auf deren Schnittstellen oder die Durchführbarkeit von Prozessschritten basierend auf den Fähigkeiten von Ressourcen untersucht werden können. So können sowohl die Durchführbarkeit eines gesamten Produktionsprozesses untersucht werden als auch die möglichen Durchführungsvarianten anhand von KPIs miteinander verglichen werden.**

Stichworte – Flugzeugproduktion, SysML, Automatisierung, Informationsmodell, Ressourcenmodellierung

I. Digitale Modellierung von Ressourcen in der Flugzuegproduktion

Passagierflugzeuge sind Systeme, deren hohe Komplexität sich aus ihrer physischen Größe und der Vielfalt an technischen Disziplinen ergibt, die in der Entwicklung beteiligt sind. Hinzu kommt eine große Variabilität, die durch den Endkunden gefordert wird. Dieser hat zum Beispiel je nach Einsatzzweck genaue Anforderungen an das Layout der Kabine.

Auch Aspekte, die zur Zeit der Produktion gesetzt sind, wie die Art des Antriebs, können in der Entwurfsphase noch offen sein. Ein elektrischer Antrieb hätte beispielsweise große Auswirkungen auf die Klimaanlage, da diese bei Einsatz von konventionellen Strahltriebwerken über den Verdichter des Triebwerks versorgt wird. Da gerade Verkehrsflugzeuge über lange Zeiträume entwickelt werden, können sich weitere Anforderungen durch externe Einflüsse, wie gesetzliche Beschränkungen, ändern. Außerdem können einzelne technische Problemstellungen durch den Einsatz von Neuentwicklungen gelöst werden.

Mit Hilfe von Digitalisierungstechniken können hierzu benötigte Modelle von Produkten mit der gewünschten Detaillierungstiefe und Variabilität erstellt werden. Jedoch muss ebenfalls die Komplexität der benötigten Produktionsumgebung beachtet werden. Auch diese soll geplant werden, basierend auf der digitalen Beschreibung der herzustellenden Produkte, der Produktionsressourcen und der dafür benötigten Prozesse [1]. Bestehende Technologien ermöglichen die Modellierung der Geometrie oder des kinematischen Verhaltens von Produktionsressourcen. Solche Modelle werden oft von Produktionstechnikherstellern, auch in digitaler Form, veröffentlicht. In einer Planungssoftware kann dann eine Produktionsumgebung aus einzelnen Ressourcenmodellen zusammengestellt werden. Jedoch ergibt sich dadurch oft ein hoher Zeit- und Kostenaufwand, der in frühen Engineeringphasen vermieden werden sollte, da die Modelle in diesen Phasen häufigen Änderungen unterliegen. In dieser Phase werden Modelle der Produktionsressourcen benötigt, die von Geometrie und Kinematik abstrahieren. Modelbasierte Ansätze ermöglichen eine schnellere und effektivere Reaktion der Planer auf die zahlreichen Anforderungsänderungen, die während des Entwicklungsprozesses auftreten [2]. Aber nicht nur die Reaktion auf Änderungen, sondern auch die Identifikation und Bewertung von Realisierungsalternativen sind für die System Engineers nicht leicht zu finden und erfordern oft eine mühsame manuelle Definition der Implementierungselemente [3].

Daher gewinnt die Modellierung und Verwaltung von Produktionsressourcen für die Prozess- und Ressourceneinsatzplanung für Fertigungsunternehmen immer mehr an Bedeutung [4].

Die Nutzung der Modelle ist dabei nicht allein auf die „Erstmodellierung“ der Systeme beschränkt, sondern kann im weiteren Produktlebenszyklus auch für die Identifikation von rekonfigurierbaren Fertigungsressourcen genutzt werden, die in der Luftfahrtproduktion immer wichtiger werden [5]. Um den Aufwand bei der Erstellung solcher Modelle zu reduzieren sowie eine einheitliche Struktur bei der Erstellung zu

https://doi.org/10.24405/14552

gewährleisten, stellt dieser Beitrag ein generisches Modell zur standardisierten Beschreibung von Fertigungsressourcen vor.

Der nachfolgende Beitrag ist wie folgt gegliedert: In Kapitel II werden verwandte Forschungsansätze sowie verschiedene Beschreibungsmittel vorgestellt. Anschließend wird in Kapitel III das generische Modell vorgestellt, welches in Kapitel IV für eine beispielhafte Modellierung genutzt wird. Abschließend wird in Kapitel V ein Fazit gezogen und ein Ausblick in zukünftige Weiterentwicklungspotenziale gegeben.

II. STAND DER TECHNIK

Bei der Auswahl der gewählten Modellierungssprache sind in der Literatur wesentliche Unterschiede im Detaillierungsgrad der Modellierung sowie bei den beschriebenen Anwendungsfällen zu erkennen. Als die vielversprechendsten und zugleich meistgenutzten Modellierungssprachen wurden die Web Ontology Language (OWL), die Automation Markup Language (AML) sowie die System Modelling Language (SysML) identifiziert. Die folgenden Unterkapitel stellen eine Auswahl bestehender Ansätze vor und diskutieren die Eignung für den beschriebenen Anwendungsfall.

A. Web Ontology Langugage (OWL)

Die OWL ist eine durch das World Wide Web Consortium (W3C) standardisierte, computerinterpretierbare Sprache für Semantic-Web-Anwendungen, welche es ermöglicht, komplexes Wissen als Graphen zu beschreiben [6]. Die Daten des Graphen werden in Form von Individuen und Beziehungen zwischen diesen festgehalten. Ebenfalls kann die Semantik des Graphen explizit definiert werden, indem Individuen und Beziehungen klassifiziert werden sowie definiert wird, welche Beziehungen zwischen bestimmten Klassen von Individuen bestehen können. Diese Metainformationen werden auch Ontologie genannt [7].

Im Forschungsgebiet Semantic-Web werden neben Beschreibungssprachen auch Sprachen zur Abfrage von Wissen aus OWL-Graphen (wie z.B. SPARQL [8]) oder Sprachen zur Definition von Regeln, durch die auf zusätzliches Wissen geschlussfolgert werden kann, entwickelt (z.B. SWRL [9]).

Ontologien und Wissensgraphen werden auch in der aktuellen Forschung in den Ingenieurwissenschaften, im Speziellen in der Automatisierungstechnik, angewandt.

Zum Beispiel können Ontologien genutzt werden, um Begriffe, Attribute und Beziehungen aus dem Bereich der Automatisierungstechnik und der Robotik zu beschreiben [10]. Auch Know Rob 2.0, ein Wissensverarbeitungssystem für autonome Serviceroboter, basiert auf Ontologien [11]. In der Robotik ist oft auch die Beschreibung der Umgebung, in welcher der Roboter betrieben wird, von großer Bedeutung. Die von Lemaignan et al. definierte Ontologie kann für die Beschreibung der Umwelt und der Interaktion von Menschen und Maschine genutzt werden [12]. Auch ein Beitrag von Bruno et al. befasst sich mit der Mensch-Maschine-Interaktion im speziellen Anwendungsfeld der Service-Roboter für die Pflege von hilfsbedürftigen Menschen [13].

Hildebrandt et al. stellen einen Ansatz vor, mit dessen Hilfe einzelne Aspekte cyber-physikalische Systeme (CPS), wie Ressourcenstruktur, Fähigkeiten oder Skills, mit einzelnen Ontologien beschrieben werden können, welche mithilfe einer übergeordneten Ontologie miteinander in Verbindung gesetzt werden [14].

In weiteren Beiträgen werden die Aspekte Fähigkeiten und Skills genauer betrachtet, ebenfalls basierend auf Ontologien [15, 16]. Auch Haage et al. stellen eine Reihe von Ontologien vor, die zusammen die Implementierung und Roboterfähigkeiten ermöglichen und bei der Rekonfiguration dieser Systeme helfen [17]. Diab et al. entwickeln eine Robotik-Ontologie mit dem Ziel, Wissen aus der Domäne der Aufgaben- und Pfadplanung zu inferrieren [18].

B. System Modelling Language (SysML)

Die SysML ist eine universelle grafische Modellierungssprache zur Spezifikation, Analyse, Gestaltung und Überprüfung komplexer Systeme. Sie stellt eine Teilmenge der UML 2 sowie eine Erweiterung um zusätzliche Funktionen und Diagrammtypen dar, sodass die SysML auch im Engineering komplexer physischer Systeme eingesetzt werden kann [19].

Mykoniatis et al. stellen einen modellbasierten Forschungsansatz für eine integrierte konzeptionelle Entwurfsbewertung mechatronischer Systeme unter Verwendung von SysML vor. Es werden verschiedene Ressourcenkomponenten beschrieben, sowie eine Methode vorgestellt mit deren Hilfe verschiedene Kombinationen hinsichtlich definierter Kriterien bewertet werden. Die Modellierung beschränkt sich auf die Darstellung von Komponenten und berücksichtigt weder Komponenten-schnittstellen noch Ressourcenfähigkeiten [20].

Tsuji et al. kritisieren, dass aufgrund von fehlenden standardisierten Modellen die Wiederverwendbarkeit von Systemarchitekturen für Roboter bei der Nutzung von Middleware-Plattformen wie ROS gering ist. Daher entwickeln die Autoren ein SysML-Modell für die Systementwicklung von Robotern, welches eine hohe Wiederverwendbarkeit besitzt. Der Fokus der Modellierung liegt auf der Beschreibung von Prozessen und dem Datenaustausch der einzelnen Komponenten [21].

Huckaby et al. beschreiben die Modellierung von Roboterfähigkeiten in einer Assembly Domain [22]. Der Ansatz beschreibt jedoch keine Darstellung der physischen Struktur der entsprechenden Ressourcen.

C. Automation Markup Language (AML)

Die AutomationML ist eine XML-basierte, objektorientierte Modellierungssprache. Abbildbar sind die Objekttopologie inklusive Hierarchien, Eigenschaften und Beziehungen, Geometrien und Kinematiken und die Modellierung von diskretem Verhalten. AML greift auf standardisierte und etablierte Datenformate und Normen zurück [23].

Hoang et al. nutzen die AML zur Implementierung eines maschineninterpretierbaren Fähigkeitsmodells. Das Modell soll durch den Abgleich von Produktanforderungen und Ressourcenfähigkeiten Produktionsplanungs- und Rekonfigurationsprozesse erleichtern [24].

Ferreira et al. stellen einen AML-basierten PPR-Ansatz vor, der ausführbare Ressourcen-Fähigkeiten beschreibt. Die Beschreibung der Fähigkeiten wird in einem Plug & Produce Szenario eingesetzt und mit Montageanforderungen verglichen. Durch den Aufbau von Bibliotheken wird der Aufwand bei der Erstellung der Modelle reduziert [25].

D. *Auswahl des Beschreibungsmittels*

Eine Modellierung basierend auf OWL zeichnet sich vor allem durch einen hohen Formalisierungsgrad aus. Ein hoher Freiheitsgrad in der Modellierung von Metamodell und Modellinhalten ermöglicht die Abbildung beliebigen Wissens, setzt aber ein großes Expertenwissen für den Aufbau, die Erweiterung und die Pflege der Modelle voraus. Eine grafische Repräsentation ist nicht vorgesehen, dies schränkt die Anwendbarkeit und Lesbarkeit für Laien ein. Daher wird von der Nutzung von OWL abgesehen.

Die AutomationML ist ein objektorientiertes, maschinenlesbares Datenformat, welches für Software-Werkzeug-übergreifenden Datenaustausch geeignet ist. Es können zwar domänenspezifische Bibliotheken aufgebaut und genutzt werden, allerdings ist die Modellierung auf Ressourcen beschränkt. Eine ebenfalls entscheidende Anforderung an das Beschreibungsmittel ist die Modellierung von Anforderungen sowie die Analyse, ob eine Ressource für einen bestimmten Prozess geeignet ist.

Die SysML ist ebenfalls eine objektorientierte Modellierungssprache, welche eine diagrammbasierte, grafische Repräsentation beinhaltet. Dies erleichtert die Anwendbarkeit und Lesbarkeit speziell für Laien. Profile ermöglichen eine beliebige Erweiterung der Modelle. Viewpoints können genutzt werden, um die modellierten Ressourcen domänenspezifisch zu filtern und darzustellen. Das Modellieren und Überprüfen von Anforderungen ist eine Kernkompetenz von SysML und gewährleistet die richtige Auswahl der Ressourcen. Tools, die SysML implementieren, wie z.B. Cameo Systems Modeler, stellen zusätzliche Funktionen, beispielsweise zur Simulation oder Validierung der Modelle, bereit. Die geringere Ausdrucksmächtigkeit im Vergleich zu OWL ist ein Nachteil, jedoch für den Aufbau der Ressourcenmodelle nicht problematisch, da die darzustellenden Ressourcen physikalische Systeme sind, auf die sich die SysML beschränkt.

III. Beschreibung des generischen Modells

Die Analyse der Literatur zeigt, dass SysML eine geeignete Modellierungssprache für die Erstellung eines generischen Modells für die Darstellung von Produktionsressourcen ist. Die Struktur des Modells sowie die Darstellungsart der Inhalte wird durch die objektorientierte Darstellung von SysML kaum eingeschränkt. So ist sichergestellt, dass alle Inhalte, die für die anfangs genannten Anwendungsfälle des Modells notwendig sind, dargestellt werden können.

Neben diesem Aspekt hat jedoch auch die Akzeptanz des Modells durch die nutzenden Planer eine hohe Priorität. Diese soll durch eine Orientierung der Struktur sowie der Inhalte des Modells an vorhandenen und etablierten Standards und Normen sichergestellt werden. Durch eine ähnliche Struktur können Daten aus bestehenden Datenquellen in das Modell übertragen oder aus dem Modell in einer Form ausgegeben werden, die für andere Anwendungen lesbar ist. Die referenzierten Normen und Standards stammen aus den Bereichen Automatisierungstechnik und Fertigungstechnik. Der aus den Standards resultierende Aufbau des Modells sowie die Erweiterung um neue Aspekte und Verknüpfungen werden in den folgenden Unterkapiteln beschrieben.

A. *Grundstruktur des Modells nach PPR*

Obwohl der Fokus des Modells auf der Darstellung von Ressourcen liegt, wird als oberste Ebene eine weitere Abstraktion eingeführt. Das PPR-Modell (Produkte, Prozesse und Ressourcen) ist eine gängige Darstellung in der Produktionstechnik und wird auch vom Netzwerk Plattform Industrie 4.0 empfohlen [26], wo es zusätzlich um Capabilities erweitert wird. Das in SysML übertragene Modell wird in Abbildung 1 dargestellt und bildet die Basis für das hier vorgestellte Ressourcenmodell.

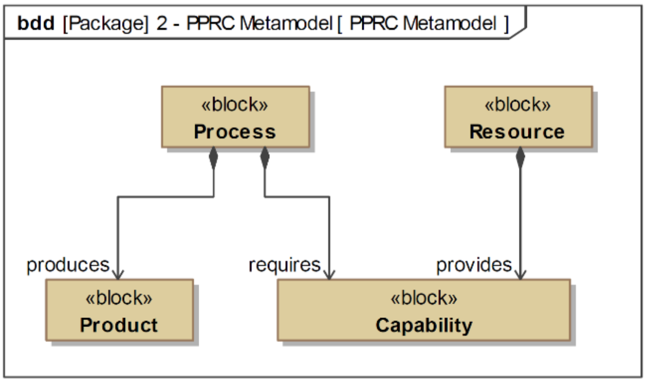


Abbildung 1: In SysML übertragenes PPR-Modell, erweitert um Capabilities [26].

Über den Block Capability entsteht die Verbindung zu den Blöcken Process und Product. Diese Verbindung ist zunächst nicht erforderlich, soll aber später genutzt werden, um automatisiert abzufragen, welche Ressourcen für die Durchführung eines Prozesses und damit die Herstellung eines Produktes geeignet sind.

B. *Klassifizierung von Resourcen und technische Spezifikation*

Als Grundgerüst für die Struktur des Modells wird der OPC-UA-Standard herangezogen. Dieser besteht aus mehreren Bestandteilen, sogenannten Specifications, die unter anderem ein Informationsmodell definieren, mit dem industrielle Kommunikationsarchitekturen dargestellt werden können [27]. Das grundlegende Meta-Modell wird sehr abstrakt beschrieben, z.B. durch die Definition von Datentypen [28], während erweiternde Specifications praxisnahe Meta-Modelle für die Darstellung konkreter Hard- und Software bereitstellen [29]. Zusätzlich besteht für industrielle Vereinigungen durch sogenannte Companion-Specifications die Möglichkeit, OPC UA domänenspezifisch zu erweitern [27], z.B. im Bereich der Robotik [30].

Im hier dargestellten Ressourcenmodell wird auf die Specification für Devices [29] und auf die Companion-Specification für Robotics [30] zurückgegriffen. Beide hängen miteinander zusammen und werden für das Ressourcenmodell in SysML übertragen. Abbildung 2 zeigt einen Ausschnitt aus dem Ressourcenmodell, das die Robotics-Companion-Specification abbildet.

Im Bereich der industriellen Kommunikation ist OPC UA ein anerkannter Standard, sodass durch die Orientierung an diesem die Akzeptanz des Ressourcenmodells unter den später nutzenden Ingenieurinnen und Ingenieuren gesichert werden kann. Ebenfalls kann die Beschreibung der Kommunikationsinfrastruktur später automatisiert aus dem SysML-Modell in Form eines OPC-UA-Informationsmodells ausgegeben und für die Implementierung der realen Infrastruktur verwendet werden.

Nachteilig ist, dass der OPC-UA-Standard auf die Darstellung von Netzwerkarchitekturen fokussiert und weniger die physische Struktur von Ressourcen berücksichtigt wird. Das OPC-UA-Informationsmodell ist aber grundsätzlich erweiterbar. Der Standard stellt daher das Grundgerüst für die Modellierung der physischen Strukturen dar, muss jedoch um einige Aspekte erweitert werden.

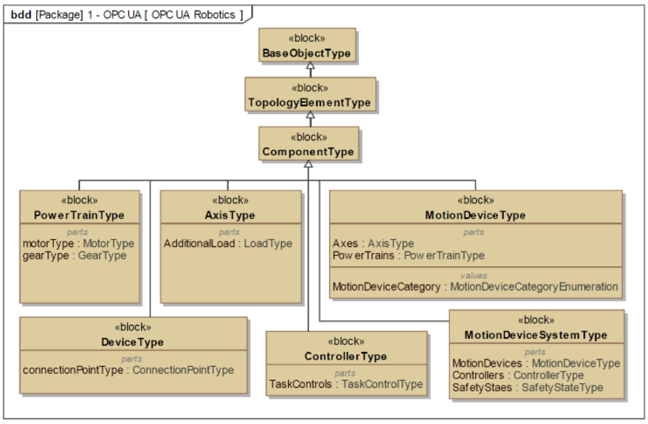


ABBILDUNG 2: NACHBILDUNG DER OPC UA COMPANION SPECIFICATION FOR ROBOTICS IN SYSML.

Dafür wurde ein Interface definiert, welches von physischen Komponenten (wie z.B. technischen Ressourcen) implementiert werden kann. Ein Interface ist hier im Sinne der objektorientierten Programmierung als eine abstrakte Superklasse zu verstehen, die von spezifischeren Klassen implementiert werden kann. Die physische Komponente erbt vom Interface IPhysicalComponentType typische Eigenschaften, wie z.B. die Masse (mass) oder die Staubschutzklasse (IP rating), was in ABBILDUNG 3 dargestellt wird.

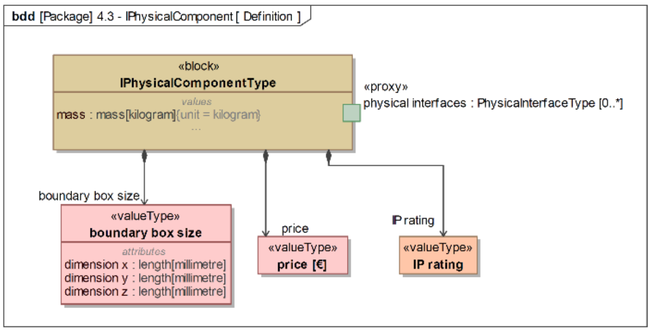


ABBILDUNG 3: INTERFACE IPHYSICALCOMPONENTTYPE ZUR VERERBUNG VON EIGENSCHAFTEN PHYSIKALISCHER KOMPONENTEN.

C. Schnittstellen

Neben der Beschreibung der physischen Komponenten einer Ressource muss auch die Komptabilität dieser mit anderen Ressourcen darstellbar sein. Dies wir mit Hilfe von Schnittstellen umgesetzt, welche zunächst in mechanische Schnittstellen zur Kraftübertragung, elektrische Schnittstellen zur Stromversorgung und Kommunikationsschnittstellen untergliedert werden. Weitere Schnittstellen, z.B. zur Beschreibung von Versorgung mit Hydraulikflüssigkeit, Kühlmittel oder Druckluft sind aktuell kein Bestandteil und sollen in der weiteren Umsetzung berücksichtigt werden.

Da gerade zum aktuellen Zeitpunkt Anwendungen im Bereich der Robotik im Fokus stehen, wird zunächst die ISO 9409 zur Beschreibung einer Unterklasse von mechanischen Schnittstellen referenziert. Diese Norm beschreibt Abmaße und Bezeichnungen typischer mechanischen Schnittstellen für die Installation und Austauschbarkeit von Endeffektoren in der Robotik. Durch eine spezielle Codierung hilft die Norm, passende Endeffektoren zu identifizieren. [31, 32]

Für elektrische Steckverbindungen existieren einige Normen, die in das Modell einfließen. Beispiele sind RJ-45 oder IEC 19/20 für Steckverbindungen. Diese dienen der Beschreibung von elektrischen Schnittstellen zur Stromversorgung bzw. kabelgebundenen Kommunikation. Auch für kabellose Kommunikation existieren Standards, wie zum Beispiel der Standard IEEE 802.11.

Kommunikationsprotokolle sind meist unabhängig von der physischen Umsetzung der Verbindung und können daher Kommunikationsschnittstellen allgemein zugeordnet werden. Hier wird ein Bezug zum Standard OPC UA DI, zu sogenannten ConnectionPoints, hergestellt. Eine Auflistung konkreter, gängiger Kommunikationsprotokolle der Automatisierungstechnik ist nicht in OPC UA vorhanden. Hier wird auf das OSI-Modell [33] zurückgegriffen, mit dem nach einem Layer-Prinzip verschiedene Kommunikationsprotokolle beschrieben werden können, auch industrielle Protokolle wie PROFINET [34].

D. Fähigkeiten

Neben der Beschreibung der physischen Struktur und Schnittstellen ist die Beschreibung der Ressourcen-Fähigkeiten, in ABBILDUNG 1 als Capability beschrieben, ein essenzieller Bestandteil, um geeignete Ressourcen oder Konfigurationen zu identifizieren. Die Untergliederung der Klasse ist in ABBILDUNG 4 dargestellt. Im Fokus des Modells steht die Beschreibung von Produktionsressourcen, sodass auf etablierten Normen dieser Domäne zurückgegriffen wurde, um eine eindeutige Taxonomie zu definieren.

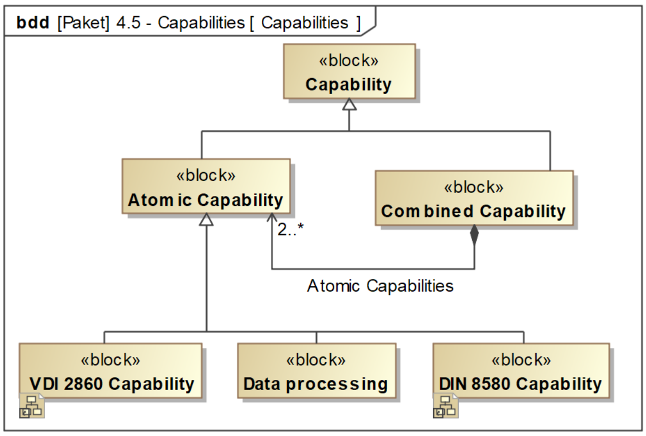


ABBILDUNG 4: UNTERGLIEDERUNG DER KLASSE CAPABILITY.

Die DIN 8580 [35] definiert und erläutert Grundbegriffe im Gesamtbereich der Fertigungsverfahren. Sie bildet die Grundlage für den Aufbau eines Ordnungssystem durch die Untergliederung in Haupt- und Untergruppen. Die VDI 2860 [36] definiert und unterteilt das Handhaben von Material und Produkten. Sie gliedert Prozesse des Handhabens in fünf Hauptgruppen, welche wiederum in Teilfunktionen unterteilt werden. Ziel dabei ist es, die Planung und Auslegung solcher Prozesse zu erleichtern.

Zunächst ist zwischen einer Atomic Capability und einer Combined Capability zu unterscheiden. Eine Ressourcen-Komponente, welche genau über eine atomare Fähigkeit verfügt, besitzt eine Atomic Capabilty, während eine Komponente mit mindestens zwei Capabilties ein Combined Capability besitzt.

Dem gegenüber steht ein Prozess, welcher aus mehreren Prozessschritten besteht. Jeder einzelne Schritt benötigt stets genau eine Capabiltiy für seine Umsetzung. Ein Prozesseschritt, welcher mehr als eine Capabilty benötigt, wird aufgeteilt und als parallellaufende Prozessschritte modelliert. Neben der Beschreibung der Capabilites sind auch die entsprechenden Prozessparameter zu beschreiben. Diese können zum einen den Normen entnommen, zum anderen durch Experten-Interviews und durch Durchsicht von entsprechenden Standard Operation Instructions (SOI) identifiziert werden. Nur wenn die Capabilty und der entsprechende Parametersatz die Prozessanforderungen erfüllen kann, ist die Ressource zur Prozessumsetzung geeignet.

Eine detailliertere Beschreibung des Prozessmodells wird in einer zukünftigen Veröffentlichung vorgestellt.

IV. Beispielhafte Umsetzung

Zur Veranschaulichung des Modells wird eine Ressource beispielhaft modelliert. Dabei handelt es sich um einen Industrieroboter, exemplarisch einen *UR10* des Herstellers *Universal Robots*. Das definierende SysML-Diagramm (*Block Definition Diagram, bdd)* wird in Abbildung 5 dargestellt. Um eine Ressource in der Ressourcenbibliothek anzulegen, wird diese als Unterklasse einer kategorisierenden Klasse (hier: *IndustryRobot*) angelegt. Eine weitere Systematisierung ist denkbar, z.B. die Definition einer Klasse für Roboter einer Produktlinie. Die hier definierte Klasse *UR10* überschreibt die Standardwerte verschiedener Eigenschaften, die sie von *IndustryRobot* oder abstrakteren Klassen erbt. Eine Angabe zur Staubschutzklasse (*IP rating*) wird z.B. von der Klasse *IPhysicalComponentType* geerbt und hier mit IP54 überschrieben. Auch komplexere Angaben können überschrieben werden, z.B. die Ressourcenfähigkeiten (*provides*). In diesem Fall wird dem Roboter die Fähigkeit Führen (nach der Definition der VDI Richtlinie 2860) mit einer Genauigkeit von 100 µm zugeordnet.

Auf die gleiche Weise ist auch die Modellierung anderer Komponenten wie Tools, Sensoren oder Controllern möglich.

Die in der Ressourcenbibliothek angelegten Komponenten können für die Modellierung eines übergeordneten Systems in einem weiteren bdd genutzt werden. In diesem Modellierungsbeispiel wird, wie in Abbildung 6 zu sehen, ein Robotersystem, bestehend aus einem UR10, einem 2D Laser Scanner und einen Greifer-Tool modelliert.

Während der UR10 als MotionDevice feststeht, stehen je zwei Sensoren und Tools als mögliche Komponenten zur Verfügung. Außerdem wurde eine maximale Masse des Gesamtsystems von 33 kg als Requirement für den Anwendungsfall definiert. Das Parametric Diagram ermöglicht durch Constraint Blocks die Modellierung von mathematischen und logischen Zusammenhängen wie hier die Berechnung der Gesamtmasse. Die verschiedenen Systemvarianten können anschließend in einer Instance Table implementiert und mit Hilfe des Cameo Simulation Tool-Kit ausgewertet werden.

Der *Instance Table* aus Abbildung 6 ist zu entnehmen, dass die Möglichkeit 3 aufgrund ihrer Gesamtmasse von 34.05 kg nicht für den Einsatzzweck in Frage kommt.

V. Fazit und Ausblick

Das in Kapitel IV gezeigte Beispiel stellt dar, wie Ressourcen modelliert werden können.

Auch die Modellierung verschiedener Systemvarianten konnte gezeigt werden, wenn auch nur an einem einfachen Anwendungsbeispiel. Die Anwendbarkeit des Models bei der Modellierung komplexerer industrieller Systeme sowie der Überprüfung komplexerer Anforderungen wird zukünftig überprüft.

Weiterhin wurden automatisierte Auswertungen des Modells bisher nicht behandelt und nur prototypisch implementiert. Geplant sind Auswertungen, welche Ressourcen, basierend auf ihren Schnittstellen, miteinander kompatibel sind und welche Prozesse sie, basierend auf ihren Fähigkeiten, durchführen können. Eine Kombination beider Auswertungen ist ebenfalls sinnvoll, da industrielle Ressourcen oft zusammengesetzt sind (z.B. ein Roboterarm mit einem Greifer) und Prozesse oft nur durch kombinierte Fähigkeiten (hier: *Bewegen* und *Greifen*) realisierbar werden. Um beliebig

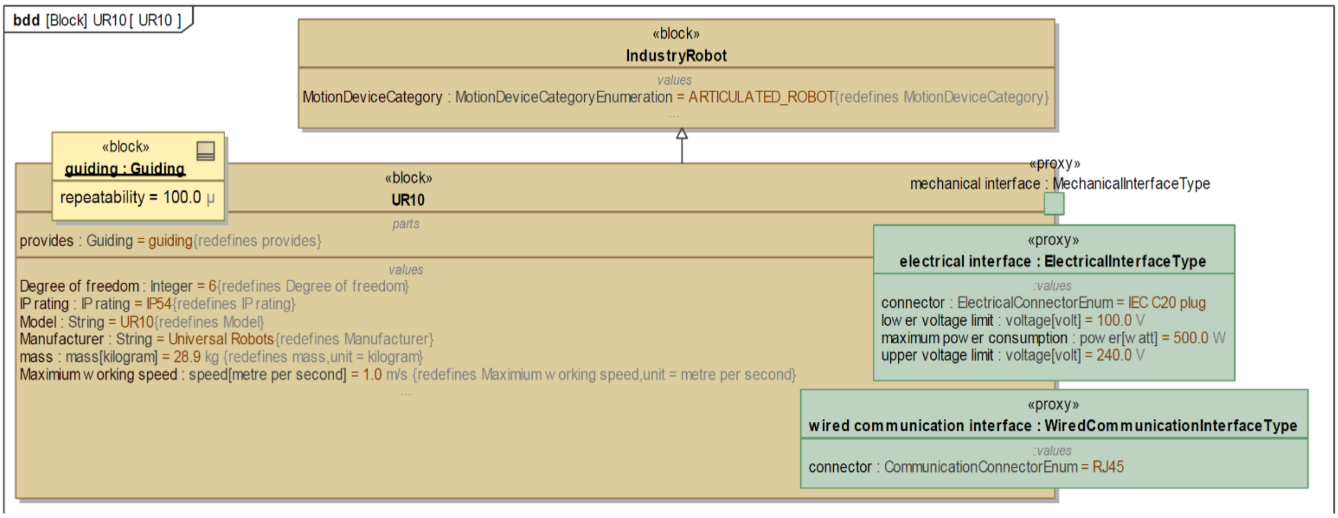
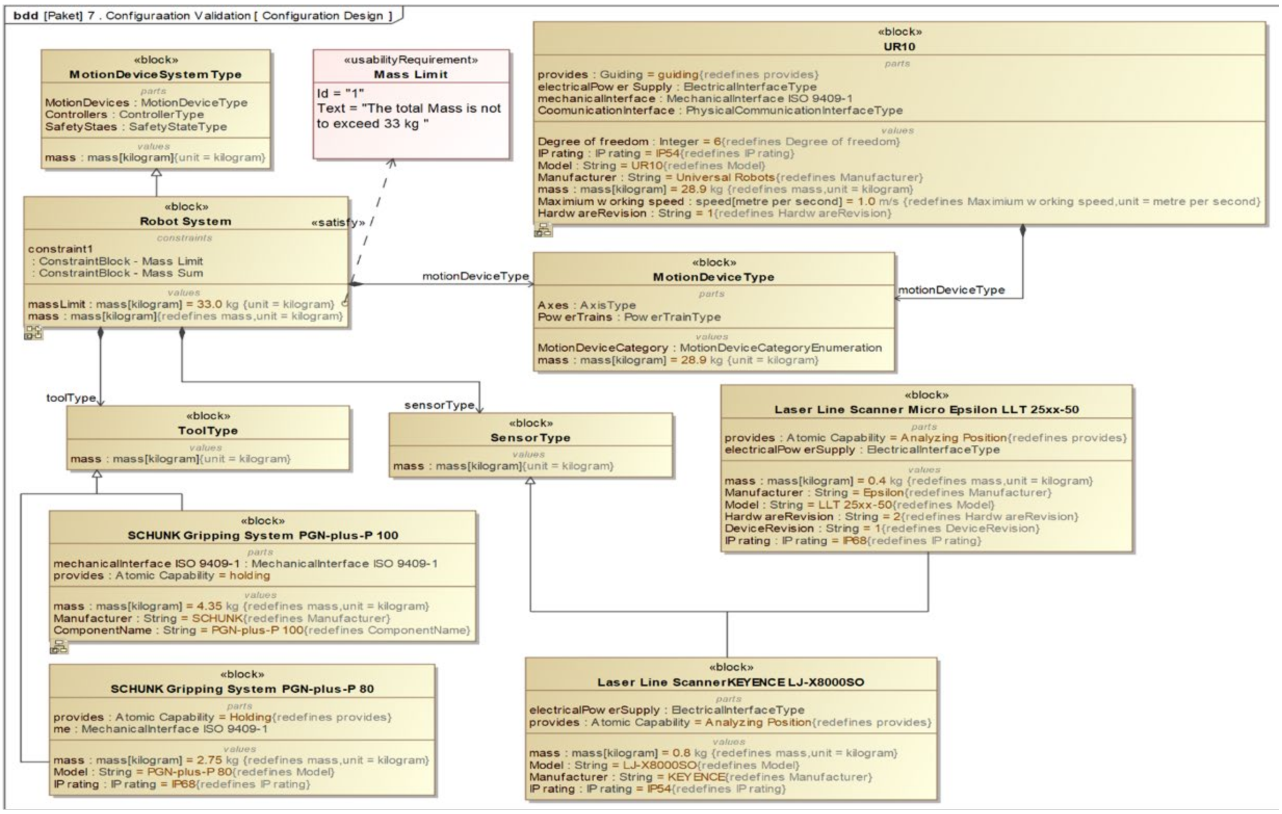


Abbildung 5: SysML Block Definition Diagram zur Spezifikation der Ressource UR10 (zu besseren Lesbarkeit werden einige Eigenschaften und Schnittstellen verkürzt dargestellt).



#	Name	massLim mass[kilo	mass : mass[kilogra	toolType : ToolType	toolType.mass : mass[kilogram	sensorType : SensorType	sensorType : mass[kilog	motionDeviceTy : MotionDeviceTy	motio :
1	robot System	33 kg	32.75 kg	schunk gripping system pgn-plus-p 100 : SCHUNK Gripping System PGN-plus-P 100	4.35 kg	laser Line Scanner Micro Epsilon LLT 25xx-5	0.4 kg	ur104 : UR10	28.9 kg
2	robot System1	33 kg	32.05 kg	schunk gripping system pgn-plus-p 80 : SCHUNK Gripping System PGN-plus-P 80	2.75 kg	laser Line Scanner Micro Epsilon LLT 25xx-5	0.4 kg	ur101 : UR10	28.9 kg
3	robot System2	33 kg	34.05 kg	schunk gripping system pgn-plus-p 1001 : SCHUNK Gripping System PGN-plus-P 100	4.35 kg	laser Line Scanner 23 : Laser Line Scanner 2	0.8 kg	ur102 : UR10	28.9 kg
4	robot System3	33 kg	32.45 kg	schunk gripping system pgn-plus-p 801 : SCHUNK Gripping System PGN-plus-P 80	2.75 kg	laser Line Scanner 24 : Laser Line Scanner 2	0.8 kg	ur103 : UR10	28.9 kg

ABBILDUNG 6. MODELLIERUNG VERSCHIEDENER RESSOURCEN-KOMPONENTEN KOMBINATION (OBEN) SOWIE DIE AUSWERTUNG DER GESAMTMASSE INNERHALB EINER INSTANCE TABLE (UNTEN)

komplexe, logische Abfragen an Informationsmodelle zu stellen, ist SPARQL eine geeignete Abfragesprache. Eine Methode, die den Zugriff auf Informationen aus einer beliebiger Software in Form eines Graphen ermöglicht [37], wurde anhand des Ressourcenmodells umgesetzt. In ersten Versuchen wurden einfache Abfragen gestellt. Da SPARQL komplexe logische Abfragen zulässt, ist zu erwarten, dass die benötigten Informationen über die genannte Schnittstelle abfragbar sind.

Zum aktuellen Zeitpunkt ist der Aufwand für die Modellierung von Ressourcen aufgrund viel manueller Arbeit hoch. Es ist daher notwendig zu untersuchen, ob Informationen über Ressourcen auch aus bestehenden Quellen automatisiert übertragen werden können.

DANKSAGUNG

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt iMOD].

REFERENCES

[1] F. Gehlhoff *et al.,* “Challenges in Automated Commercial Aircraft Production,” *IFAC-PapersOnLine*, vol. 55, no. 2, pp. 354–359, 2022.

[2] J. D'Ambrosio and G. Soremekun, “Systems engineering challenges and MBSE opportunities for automotive system design,” in *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 2017.

[3] P. Z. Chadzynski, B. Brown, and P. Willemsen, “Enhancing Automated Trade Studies using MBSE, SysML and PLM,” *INCOSE International Symposium*, vol. 28, no. 1, pp. 1626–1635, 2018.

[4] E. M. Sanfilippo *et al.,* “Modeling Manufacturing Resources: An Ontological Approach,” in *IFIP Advances in Information and Communication Technology, Product Lifecycle Management to Support Industry 4.0*, P. Chiabert, A. Bouras, F. Noël, and J. Ríos, Eds., Cham: Springer International Publishing, 2018, pp. 304–313.

[5] R. Arista, F. Mas, D. Morales-Palma, and C. Vallellano, “Industrial Resources in the design of Reconfigurable Manufacturing Systems for aerospace: A systematic literature review,” *Computers in Industry*, vol. 142, p. 103719, 2022.

[6] W3C OWL Working Group, “OWL 2 Web Ontology Language,” Accessed: Aug. 3 2022. [Online]. Available: https://www.w3.org/TR/owl2-overview/

[7] R. Neches *et al.,* “Enabling Technology for Knowledge Sharing,” *AI Magazine*, vol. 12, no. 3, pp. 36–56, 1991.

[8] E. Prud’hommeaux and A. Seaborne, “SPARQL Query Language for RDF,” W3C Recommendation, W3C, 2008. Accessed: Aug. 3 2022. [Online]. Available: http://www.w3.org/TR/2008/REC-rdf-sparql-query-20080115/

[9] I. Horrocks, P. F. Patel-Schneider, H. Boley, S. Tabet, B. Grosof, and M. Dean, “SWRL: A Semantic Web Rule Language,” Accessed: Aug. 3 2022. [Online]. Available: https://www.w3.org/Submission/SWRL/

[10] C. Schlenoff *et al.,* “An IEEE standard Ontology for Robotics and Automation,” in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012.

[11] M. Beetz, D. Bessler, A. Haidu, M. Pomarlan, A. K. Bozcuoglu, and G. Bartels, “Know Rob 2.0 — A 2nd Generation Knowledge Processing Framework for Cognition-Enabled Robotic Agents,” in *2018 IEEE International Conference on Robotics and Automation (ICRA)*, 2018.

[12] S. Lemaignan, R. Ros, L. Mösenlechner, R. Alami, and M. Beetz, “ORO, a knowledge management platform for cognitive architectures in robotics,” in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010.

[13] B. Bruno *et al.,* “Paving the way for culturally competent robots: A position paper,” in *2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2017.

[14] C. Hildebrandt *et al.,* “Ontology Building for Cyber–Physical Systems: Application in the Manufacturing Domain,” *IEEE Trans. Automat. Sci. Eng.*, vol. 17, no. 3, pp. 1266–1282, 2020.

[15] A. Kocher *et al.,* “Automating the Development of Machine Skills and their Semantic Description,” in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Vienna, Austria, 2020, pp. 1013–1018.

[16] A. Kocher, C. Hildebrandt, L. M. Da Vieira Silva, and A. Fay, “A Formal Capability and Skill Model for Use in Plug and Produce Scenarios,” in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Vienna, Austria, 2020, pp. 1663–1670.

[17] M. Haage, J. Malec, A. Nilsson, K. Nilsson, and S. Nowaczyk, “Declarative-knowledge-based reconfiguration of automation systems using a blackboard architecture,” in *Eleventh Scandinavian Conference on Artificial Intelligence*: IOS Press, 2011, pp. 163–172.

[18] M. Diab, A. Akbari, M. Ud Din, and J. Rosell, “PMK-A Knowledge Processing Framework for Autonomous Robotics Perception and Manipulation,” *Sensors*, vol. 19, no. 5, p. 1166, 2019.

[19] Object Management Group (OMG), “OMG Systems Modeling Language (OMG SysML™),” 2019. Accessed: Aug. 3 2022. [Online]. Available: https://www.omg.org/spec/SysML/1.6/PDF

[20] K. Mykoniatis, A. Angelopoulou, A. S. Akbas, and P. A. Hancock, “Multi-method modeling and simulation of a face detection robotic system,” in *2016 Annual IEEE Systems Conference (SysCon)*, 2016.

[21] H. Tsuji *et al.,* “Reusable robot system for display and disposal tasks at convenience stores based on a SysML model and RT Middleware,” *Advanced Robotics*, vol. 34, 3-4, pp. 250–264, 2020.

[22] J. Huckaby and H. I. Christensen, “A case for SysML in robotics,” in *2014 IEEE International Conference on Automation Science and Engineering (CASE)*, Taipei, 2014, pp. 333–338.

[23] Rainer Drath, Ed., *AutomationML: A Practical Guide*. Berlin, Boston: De Gruyter Oldenbourg, 2021.

[24] X.-L. Hoang and A. Fay, “A Capability Model for the Adaptation of Manufacturing Systems,” in *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2019.

[25] P. Danny, P. Ferreira, N. Lohse, and M. Guedes, “An AutomationML model for plug-and-produce assembly systems,” in *2017 IEEE 15th International Conference on Industrial Informatics (INDIN)*, 2017.

[26] A. Bayha, J. Bock, B. Boss, C. Diedrich, and S. Malakuti, “Describing Capabilities of Industrie 4.0 Components: Joint White Paper between Plattform Industrie 4.0, VDI GMA 7.20, BaSys 4.2,” 2020.

[27] *OPC 10000-1 OPC Unified Architecture Part 1: Overview and Concepts,* OPC Foundation.

[28] *OPC 10000-5 OPC Unified Architecture Part 5: Information Model,* OPC Foundation.

[29] *OPC 10000-100 OPC Unified Architecture Part 100: Devices,* OPC Foundation, London.

[30] *OPC 40010-1 OPC UA for Robotics Part 1: Vertical Integration: Part 1: Vertical Integration,* OPC Foundation.

[31] *ISO 9409-1 Manipulating industrial robots - Mechanical interfaces - Part 1: Plates,* International Organization for Standardization, Geneva, Switzerland, London.

[32] *ISO 9409-2 Manipulating industrial robots - Mechanical interfaces - Part 2: Shafts,* International Organization for Standardization, Geneva, Switzerland, London.

[33] M. M. Alani, “OSI Model,” in *Guide to OSI and TCP/IP Models*: Springer, Cham, 2014, pp. 5–17. Accessed: Aug. 28 2022. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-319-05152-9_2

[34] M. Popp, *Das PROFINET IO-Buch: Grundlagen und Tipps für den erfolgreichen Einsatz,* 2nd ed. Berlin, Offenbach: VDE Verlag, 2010.

[35] *DIN 8580: Fertigungsverfahren –Begriffe, Einteilung,* DIN-Normenausschuss Technische Grundlagen (NATG), DIN-Normenausschuss Werkstofftechnologie (NWT), 2020.

[36] *VDI 2860: Montage- und Handhabungstechnik Handhabungsfunktionen, Handhabungseinrichtungen, Begriffe, Definitionen, Symbole,* Verein Deutscher Ingenieure.

[37] M. Weigand and A. Fay, “Creating Virtual Knowledge Graphs from Software-Internal Data,” *IECON 2022 – 48th Annual Conference of the Industrial Electronics Society*.

Increasing the safety of rescue workers in fire events by merging fire simulations, structural models, and artificial intelligence

Wolfgang Weber*,
Kandekar Chaitanya, Max Rottmann
Professorship for Structural Analysis, Helmut Schmidt University / University of the Federal Armed Forces Hamburg
Hamburg, Germany
*wolfgang.weber@hsu-hh.de

Michael Breuer,
Arulnambi Palani
Professorship for Fluid Mechanics, Helmut Schmidt University / University of the Federal Armed Forces Hamburg
Hamburg, Germany

Oliver Niggemann,
Artur Liebert
Professorship for Computer Science in Mechanical Engineering, Helmut Schmidt University / University of the Federal Armed Forces Hamburg
Hamburg, Germany

Abstract **– In the event of a fire, rescue forces must be able to evacuate as many people as possible from the burning building with minimal risk to themselves. On the one hand, this requires knowledge of where people to be rescued are located in the building, and on the other hand which escape routes are available. As a result of the fire event, heat-related material degradation occurs, which can lead to (sub-)structural failure. As a consequence, some rescue routes may be obstructed during the course of the rescue operation, so that the rescue forces need information about (still) possible rescue routes. This requires a multidisciplinary approach: Fire simulations form the basis for the description of the material behavior, from which the structural failure can be determined. If these computational data are analyzed by means of machine learning methods, a real-time prediction of potential rescue routes is possible in case of fire events in comparable buildings. In the DTEC project Kibidz, especially public buildings are investigated, so that a cataloging of comparable building types can take place and generally valid methods to be developed in the project can be specified for these building types. In this paper, first research results are presented.**

I. Introduction

According to the EU Fire Safety Guide each year approximately 5000 people are killed due to building fires [1]. Although deep investigations regarding fire simulation (fluid mechanics), material degradation (micro-mechanics), and successive collapse of buildings (structural analysis) took place especially after the tragic incident of 11th September 2001, there is still a lack of knowledge in combining these different approaches. Another issue in increasing the safety of rescue workers and those to be rescued during fire events is the necessity of real-time analyses, whereas the major focus in research so far is on analyzing critical situations after the incident. However, real-time simulations combining advanced methods of fluid mechanics, micro-mechanics, and structural analysis are still limited by the computational power available. Thus, the authors of the present contribution follow another approach: Further developing the techniques of fluid mechanics, micro-mechanics, and structural analysis as well as increasing the respective reliability, provide tools for a fast data exchange between these techniques in order to obtain both realistic and time-efficient simulation results. These simulation results serve as input data for machine learning (ML) approaches. Hence, numerous numerical experiments need to be conducted increasing the need for both realistic and time-efficient simulations at different scales. By means of artificial neural networks, general characteristics of fire events and the resulting consequences for the reliability and safety of rescue routes have to be analyzed. Once the artificial neural networks are properly trained, they allow for realistic real-time predictions based on (e.g., temperature) sensor data in the event of a fire incident. The respective predictions can be used on-site by rescue workers in order to increase their safety during the rescue campaign. This necessitates an applicability of the developed advanced methods to the concrete incident. To achieve this applicability, so-called digital twins of characteristic buildings are created. To keep these digital twins both realistic and (time-)efficient, the authors restrict themselves to standardized public buildings. The aforementioned aspects are dealt within the project KIBIDZ – *Intelligente Brandgefahrenanalyse für Gebäude und Schutz der Rettungskräfte durch Künstliche Intelligenz und Digitale Brandgebäudezwillinge*, which is thus introduced in the present contribution, too.

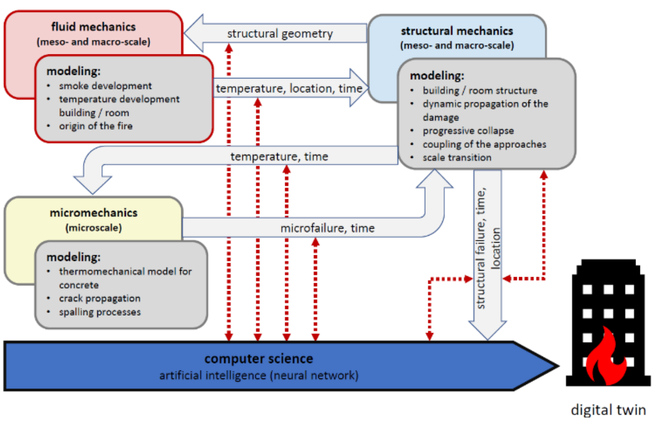


Figure 1: Interaction diagram.

https://doi.org/10.24405/14553

The outline of this contribution is as follows: In Section II major aspects of fire simulations are discussed. The methods to be developed allow for detailed simulations of the temperature evolution and flue gas propagation. The respective results serve as time-dependent input quantities for both ML approaches and thermo-mechanical analyses at the micro-scale. The main objectives of these investigations at the micro-scale are presented in Section III. Once a damage is initiated, its extent and severity may increase due to (increasing) thermal loads and/or (sudden) mechanical loads. As a consequence, a structural member may fail. Additionally, a progressive collapse may occur. These aspects are dealt within Section IV. The ML approaches which allow for both the prediction of the temperature distribution and development as well as of a successive collapse are introduced in Section V. Finally, a summary and an outlook are provided in Section VI.

II. FIRE SIMULATION AND EVOLUTION OF TEMPERATURE DISTRIBUTION

Fire, in general, causes a lot of damage to properties and the surrounding environment. Besides the fact that fire itself is dangerous for inhabitants, it can lead to heavy destructions, especially if public buildings are subjected to collapse due to the thermal load of the fire. Therefore, it is essential to study the fire characteristics and its impact on the structure of a building. The most important aspect of fire is the transfer of thermal load (in terms of heat energy) to the building structures. At first, the heat energy from the fire source is transferred to the surrounding fluid medium, i.e., the air plus the combustion products, by means of radiation from the fire itself and also from the smoke plumes that are covering the upper region of the room [2]. These hot smoke gases in-turn heat up the building through convection and conduction. Hence, the spread of the temperature along walls and ceilings plays a vital role in estimating the structural integrity of the building during a fire out-break. This study should not only help to understand the physical process of the fire but also in saving rescue workers from a partial collapse of the structure.

A. Fire Simulation

Fire simulations are carried out using the Fire Dynamics Simulator (FDS). FDS is a FORTRAN based numerical solver for large-eddy simulations (LES) using the NAVIER-STOKES-equations to solve low-speed thermally driven flows [3], especially fire. According to Rehm and Baum [4], for low-speed applications such as fire, the transport equations of fire-induced flows are simplified using the low-MACH number approximation to solve fire scenarios efficiently. Besides the governing equations, it considers a variety of sub-models (like combustion, radiation, pyrolysis, etc.). These sub-models help in emulating a realistic fire scenario. FDS is installed on the local high-performance computer and parallelized by domain decomposition and MPI. The domain is split into n domains, which is equal to the number of processors.

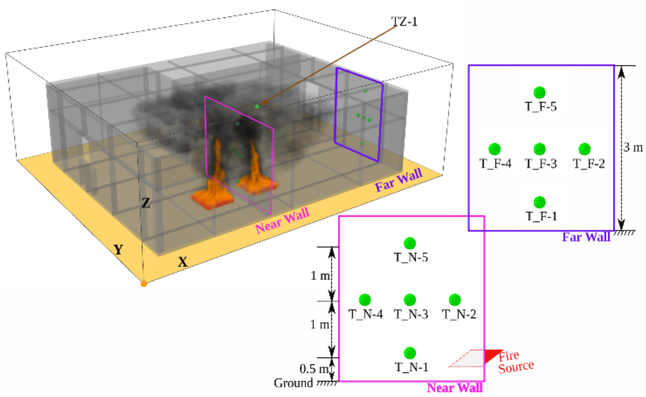


FIGURE 2: SIMULATED FIRE SCENARIO WITH GENERATION OF FIRE AND SMOKE DISPERSION SHORTLY AFTER IGNITION.

As an initial step, a basic fire scenario is considered. The setup shown in FIGURE 2 consists of two rooms with each having a fire source, a door and a window. The main objective of this model is to study the growth of fire, the dispersion of the smoke and the distribution of the temperature. In addition to the temperature also the velocity of the fluid medium and the propagation of smoke plumes and other gases are examined based on sophisticated large-eddy simulations.

B. First Results

During the set-up of the input file, the necessary output variables and planes must be chosen for post-processing the data of FDS. For example, the temperature and velocities at pre-defined planes have to be defined. In general, extracting output data for the whole domain is time consuming. Therefore, outputs are chosen sensibly at appropriate locations. Furthermore, monitoring points can be defined to assess time histories without increasing the overall run-time.

In order to provide results for the other groups, each output data is written in a particular format. The two sets of output data are the temperature within the fluid domain (at the spatial grids) and at boundary surfaces, which are delivered to the machine learning (ML) and structure group, respectively. FIGURE 2 exemplarily shows the generation of the fire and the spreading of the smoke inside the rooms. The evolution of the temperature with respect to time inside the rooms is extracted from the fire simulation and used in training the ML model of the project. The results are provided at every nodal point of the spatial grid. The development of the temperature at the surfaces of the wall due to the ignition of the fire is obtained and provided as the thermal load input for the thermo-mechanical simulations.

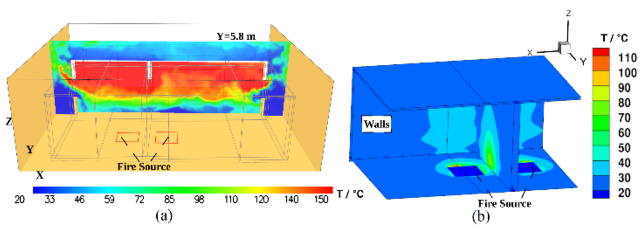


FIGURE 3: TEMPERATURE DISTRIBUTION AFTER 60 S.

FIGURE 3 (a) exemplarily depicts the distribution of the temperature along the y-plane of the room. This y-plane connects the windows of both rooms. Fig. 3 (b) shows the distribution of the temperature at the walls that are near to the fire source (right side) after 60 s.

Two sets of monitoring points are placed at the near and far (opposite) wall of the fire as shown in FIGURE 2. TZ-1 is located on the roof exactly at the center of the fire source. FIGURE 4 (top) depicts the time history plots of the near wall, whereas the second plot depicts the results on the far wall. It is evident that the temperatures in both plots are rapidly increasing due to the fire. In FIGURE 4 (top, near wall), the temperature at T_N-1 is higher than at the other points as it is located closer to the fire. The temperature curves are getting flatter with increasing distance from the fire source. Nevertheless, the temperature at TZ-1 is higher than at the points T_N-3 to T_N-5 since the hot fumes from the fire directly hit the roof and heat up the surface. In FIGURE 4 (bottom, far wall) one can observe that the points located at higher elevations possess higher temperatures than T_F-1. This is due to the accumulation of the hot smoke gases in the upper part of the room. This is especially true for the point T_F-4, which shows the strongest temperature increase since it is most strongly exposed to the smoke gases compared to the other elevated monitoring points.

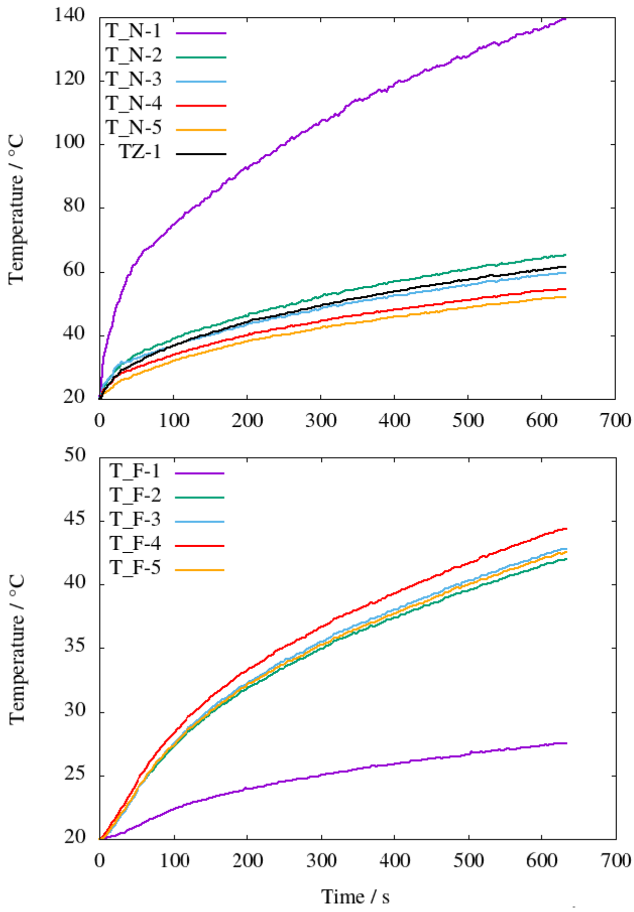


FIGURE 4: TIME HISTORY OF THE TEMPERATURE AT DIFFERENT MONITORING POINTS (SEE FIG. 2 FOR THE LOCATIONS OF THE POINTS).

C. *Future Steps*

Presently, the location of the fire is fixed and only the mass flow of the fuel is varied. In the next step, the geometry and the location of the fire source could be changed. Additionally, the spreading of the fire has to be taken into account. Furthermore, the dispersion of the smoke gases even poses a threat to the people stuck inside the building as well as to the rescue workers. Consequently, it would be useful to study the propagation of smoke within the building, thus leading to a less obstructed and safer escape route for the rescue.

III. THERMO-MECHANICAL MODELING AT THE MICRO-SCALE

At the micro-scale, a multi-field thermo-hydro-mechanical fracture model is formulated and simulated for the boundary conditions taken from the fire simulation carried out with the FDS software. Herein, concrete is modeled based on all three phases viz. solid – skeleton, liquid – liquid water, gas – water vapors and air. The main goal of this micro-scale simulation is to provide reduced stiffness at the given region due to micro-cracks resulting in material deterioration.

A. *Multi-phase Concrete Model*

Concrete is considered with all existing phases – solid, liquid and gas. Therefore, the total density ρ can be written as:

$$\rho = (1-\phi)\rho_s + \phi S_l \rho_l + \phi(1-S_l)\rho_g \,. \qquad (1)$$

Here, ϕ denotes porosity, S_l is saturation, ρ_s is density of solid, ρ_l is density of liquid, and ρ_g is density of gas. In the above equation, the first term on the right-hand side is the mass of solid skeleton, the second term is the mass of liquid water, and the third term is the mass of gas phase. Further in gas phase, water vapors and air are considered and are derived using water vapor density ρ_v and air density ρ_a. In this multi-phase concrete model, both temperature and time dependency are taken into account for porosity, saturation and all densities.

B. *Governing Equations and Implementation*

Three phase model of the concrete leads to the mass conservation equations. Mass conservation equations for each phase are as follows:

$$\begin{gathered}\frac{\partial m_s}{\partial t} = \dot{m}_{dehyd}, \\ \frac{\partial m_l}{\partial t} + \nabla \cdot (m_l v_{l-s}) = -\dot{m}_{vap} - \dot{m}_{dehyd}, \\ \frac{\partial m_v}{\partial t} + \nabla \cdot (m_v v_{g-s}) + \nabla \cdot (m_v v_{v-g}) = \dot{m}_{vap}, \\ \frac{\partial m_a}{\partial t} + \nabla \cdot (m_a v_{g-s}) + \nabla \cdot (m_a v_{a-g}) = 0.\end{gathered} \qquad (2)$$

Here, subscripts s, l, v, a, g indicate solid, liquid, vapor, air, and gas phases, respectively. The rate of change of mass due to dehydration is denoted by $\dot{m}_{dehyd}$, $\dot{m}_{vap}$ is rate of change of mass due to vaporization. Relative velocities of the respective phases are given as for example v_{1-2} is the velocity of the phase 1 with respect to phase 2. These relative velocities are modeled by using DARCY's law and FICK's law.

Mass balance equations given in Eq. (2) are further developed by substituting densities of each respective phase and by using chain rule for the time derivative. This results into primary variables as gas pressure p_g, capillary pressure p_c and temperature T. The final form of the balance equations is solved by using the finite-element method with C_0 continuous shape function for spatial discretization and NEWMARK time integration for the temporal discretization. Thereafter, each balance equation is solved in a staggered manner until global convergence is achieved.

C. *Boundary Value Problem*

A simplified one-dimensional boundary value problem is formulated according to [5] in order to simulate in staggered manner for the verification of the algorithm. A one-dimensional bar of length 20 cm is considered with 200 elements. Temperature profile according to standard fire curve [6] is given as DIRICHLET boundary condition on the left side and NEUMANN boundary condition of no fluxes on the other sides. Heat and mass transfer coefficients are taken as 18 Wm^{-2} K and 0.018 ms^{-1}, respectively. All material parameters and their temperature-dependent constitutive relations are taken from [7].

Results of the one-dimensional boundary value problem are plotted in FIGURES 5 and 6 for simulations running from 0 min up to 60 min. In FIGURE 5, temperature profile can be seen developing from the fire exposed side with a steep gradient. Temperature of the fire exposed face reaches 1200 K in 60 min while the temperature inside the concrete is still below 300 K. Temperature gradients are increasing significantly for the first 5 cm of the concrete.

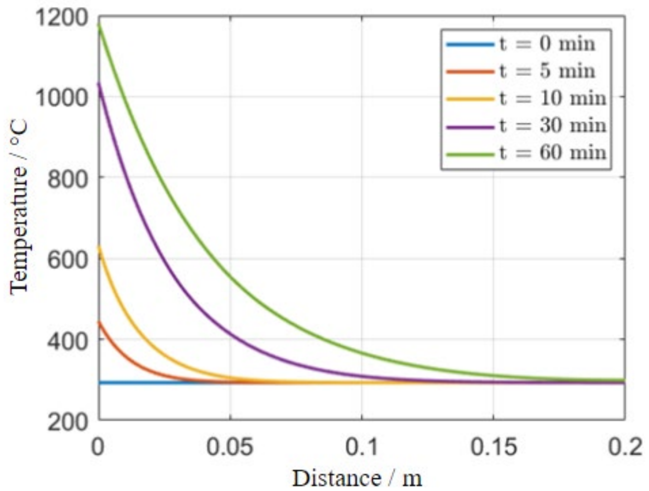


FIGURE 5: TEMPERATURE PROFILE OF THE 1D PROBLEM WITH THE LEFT FACE EXPOSED TO FIRE WITH STANDARD FIRE CURVE.

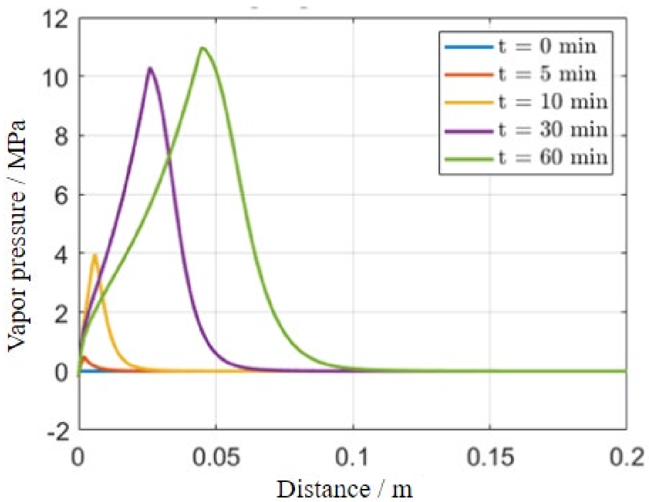


FIGURE 6: VAPOR PRESSURE PROFILE OF THE 1D PROBLEM WITH THE LEFT FACE EXPOSED TO FIRE WITH STANDARD FIRE CURVE.

In FIGURE 6, vapor pressure profiles are shown with respect to the distance at various time instances. Here it can be observed that vapor pressure peaks are increasing with respect to time and at the same time the curve is shifting towards right face side which represents colder regions. These curves are in agreement with the moisture clog theory and confirms that the vapor flux traveling towards both sides ends up forming peak pressures near the fire exposed face. This rise in vapor pressure also introduces significant pressure gradients within a small distance with respect to the total dimension of the bar.

D. *Future Steps*

This model will be extended with a phase-field fracture equation that will be solved also in a staggered manner. Fracture criteria for the phase-field equation will be based on the peak pressure limit and GRIFFITH's fracture energy. In this way, fire damage in the concrete will be computed and delivered to the macro-scale model using a scale transition algorithm.

IV. MODELING OF SUCCESSIVE FAILURE AT THE STRUCTURAL SCALE

Successive failure or progressive collapse due to fire is an important topic in the structural analysis of buildings. Especially since the devastating events of 11th September 2001 and the collapse of the World Trade Center (WTC), as well as more recent events such as the Plasco building disaster in 2017, show the extent of progressive collapse. In both cases, investigations have shown that the main cause of the collapse of the buildings could be attributed to fires and the high temperatures that accompanied them. As a result of these events, with the WTC collapse leading the way, there is a large interest in the scientific community to understand the mechanisms that trigger progressive collapse. Due to the very high cost of experiments and the highly simplified analytical solutions, which lead to inaccuracies, numerical simulations for the analysis of progressive collapses using finite-element methods (FEM) or applied element methods (AEM) are currently very common. The challenge to be met here is to build a model that provides accurate results without being too expensive from a numerical point of view. In the following, the terminology, failure mechanisms, and the general procedure of such simulations will be described.

A. *Progressive Collapse*

Progressive collapse results from the local failure of a structural element (e.g., column or beam) and the subsequent transfer of damage to other structural elements (dynamic propagation) until general structural failure [8]. This process can be seen in FIGURE 7, which shows the collapse of the Alfred P. Murrah building according to [8]. Even though the origin of the partial collapse was an explosion, the fundamental mechanisms of a progressive collapse are clearly visible here. First, a primary column fails. The lack of support from the column leads to the failure of the girder and the subsequent failure of the upper parts of the building. The characteristic of progressive collapse is that the final condition is disproportionately larger than the initial local failure [9]. Furthermore, it can usually be seen that after the failure of the first structural component, the parts that fail are in its vicinity, see also FIGURE 7.

B. *Failure Mechanism*

The failure mechanism of the structural components can be simplified to three causes. One cause is temperature change-induced thermal expansion (i), which causes the components to build up extra internal stresses in the fixed state and to exert displacements on surrounding structural elements in the simply supported state [10]. Both variants lead – directly in the affected component or indirectly in surrounding components – to increased loads and in extreme cases to failure. According to [11], the second cause results from a temperature gradient in structural elements such as ceilings and walls. In real fire scenarios, building components have warm and cold regions until the thermal equilibrium state is reached. This temperature gradient across the component (ii) in turn leads to an increase in internal stress in the component, which can lead to failure. The third cause is material degradation (iii) due to the increased temperatures, which is described in Section III. In building fires, mechanisms (i), (ii), and (iii) occur in combination and must be considered together for an accurate simulation. It must be taken into account that (i) and (ii) mainly occur on the macro-scale (building scale, component scale) and (iii) on the micro-scale (material model) and thus a multi-scale approach is necessary. The relationship between the scales is shown in FIGURE 1.

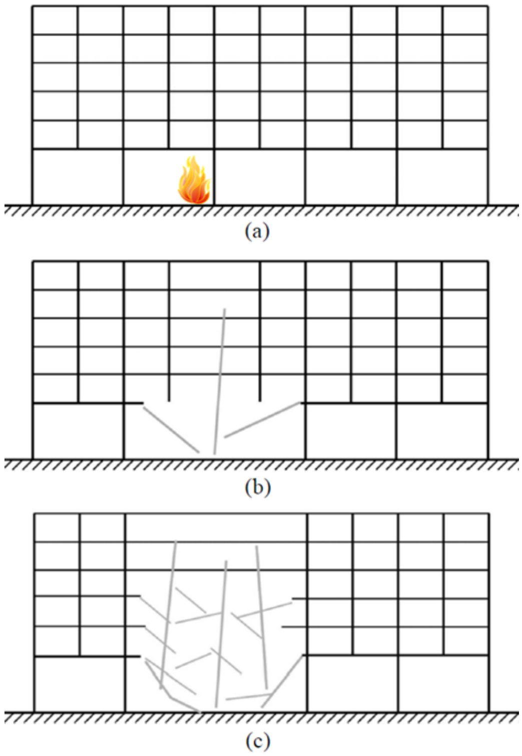


FIGURE 7: COLLAPSE OF ALFRED P. MURRAH BUILDING ACCORDING TO *[8]* (a) SOURCE OF THE COLLAPSE, (b) FAILURE OF THE FIRST ELEMENTS, (c) PROGRESSIVE (PARTIAL-) COLLAPSE.

C. Future Steps

Based on the fire simulation from Section II, which provides important temperature and smoke gas data, the local material failure can be determined in the micro-mechanical simulation (Section III). Both the temperature and smoke gas data, as well as the results of the micro-mechanical simulation, provide the input for the macro-mechanical model or structural model. In the structural model, the data are scaled to the macro-scale and used to determine the progressive collapses. The macro-model thus represents the necessary training data for the artificial neural network of Section V.

A detailed structural model (macro-scale) for burning buildings taking into account Sections II and III, and the coupling to an artificial neural network is missing so far. Especially the behavior of lightweight construction and the use of precast elements in case of fire have to be investigated. Furthermore, collapse topologies have often been considered separately, although mixed failure topologies occur under real conditions. The work should contribute to a better understanding of the phenomena mentioned [12].

V. FORECASTING TEMPERATURE AND DAMAGE EVOLUTION BY MEANS OF MACHINE LEARNING

This chapter shows current and possible future states of the development of artificial neural networks specialized on the task of temperature forecasting as well as the prediction of material behavior inside a burning room.

A. Data and Temperature Forecasting

Artificial neural networks (NN) are highly dependent on their training conditions and therefore rely heavily on their training's dataset. In order to create an effective NN, such data have to be obtained from the real world or reliable simulations. Since burning buildings are fortunately rare occasions, regarding the amount of data needed, and the reproduction of such occasions are extremely costly, within this project the desired amount of data is generated by true-to-life simulations.

Even though such simulations are just an approximation of real events, the opportunities of these simulations predominate the shortcomings. For the simulated datasets, rooms were designed with a high variation of properties like room cubature, number of doors or windows, whereas in real datasets such freedom of choice is not possible. Furthermore, numerical experiments with different boundary conditions and temperature distributions were carried out resulting in a well-balanced dataset.

The next step was to create a common interface such that the amount of simulation data can be sorted out and translated into input- and target tensors such that the NN is able to process those and learn from them. Since the numerical predictions for the fire simulations in Section II take several hours for each (numerical) experiment, the goal for the first NN was to approximate the results and, in the process, speed up their creation.

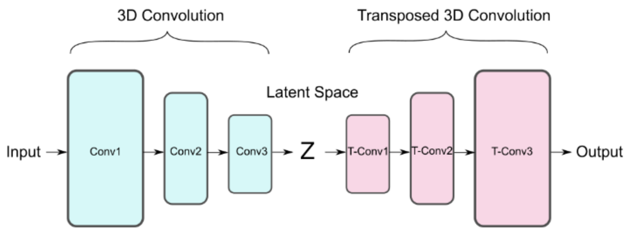


FIGURE 8: CNN ARCHITECTURE FOR FORECASTING TEMPERATURE DISTRIBUTIONS OF A BURNING ROOM.

The networks architecture was inspired by Xioxiao Guo et al. [13]. The method in [13] consists of Convolutional Neural Networks (CNN) combined with their transposed version of each layer. Each space component got its own transposed CNN layers resulting in the approximation of a steady laminar flow giving a geometry representation as input. For the suggested approach the overall architecture was adjusted such that the resulting network was capable of processing input data that represent a 3D temperature distribution of equidistant grid points. The resulting network architecture is shown in FIGURE 8.

The goal of the CNN was to forecast the temperature distribution at time $t+1$ given the distribution at time t as input. The output is then compared to the actual simulation; the mean-square error indicates the success rate of the network. Since each timestep t of the input generates outputs only one timestep ahead of the input, the CNN lacks the comprehension of proper time dependencies in the dataset. The network is focusing on the geometric behavior in the temperature alone at the current moment but is designed to be generalized in the future. As a consequence of the convolution process, grid points near the outer area show high errors, which is visible in FIGURE 9.

The method will be extended with 4D convolutional layers in order to convolute the datasets throughout the time dimension to implement a comprehension for time dependencies. Several other extension ideas like an additional one-dimensional convolution across the time dimension or additional Recurrent Neural Network layers like Gated Recurrent Units are yet to be tested.

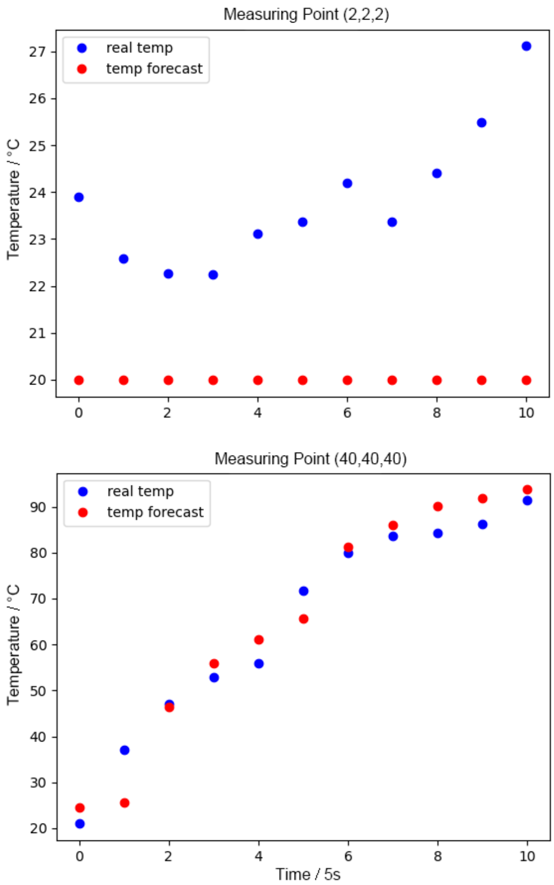


FIGURE 9: COMPARISON BETWEEN THE FAILED FORECASTING OF A POINT NEAR THE OUTER AREA (2,2,2) AND THE PROPER FORECASTING IN THE CENTRE OF THE ROOM (40,40,40).

B. *Material Behavior*

Even though the results of the proposed network can be used in order to approach the second task of forecasting damage evolution and material behavior, a second network architecture specialized for such task is needed.

Regarding anomaly detection for material behavior, several Autoencoder types were already tested and evaluated in order to detect sensor malfunction and distinguish them from material failure [14]. Based on these results, first approaches are already discussed combining two Feed Forward NN (FFNN) within the FEM to increase the simulation speed [15]. The first FFNN in this approach is trained to forecast the strain-stress behavior. Its output among other things is then processed as input by the second FFNN in order to calculate the fracture phase field behavior. Such an approach is in its infancy and will be expanded in near future. One of the end goals is ultimately the combination of both tasks, temperature forecasting and material behavior forecasting, with one generalized artificial neural network, that is suitable for variable space geometry. The possibility of such generalization is an open research question, which is targeted to answer.

VI. SUMMARY AND OUTLOOK

In this contribution, the dtec.bw project KIBIDZ is introduced. Based on the general motivation and the resulting necessary investigations at the micro-, meso-, and macro-scale, first approaches and results combining fluid mechanics, micro-mechanics, structural analyses, and artificial neural networks techniques are presented. These preliminary results show the general applicability of the joint work between the different engineering disciplines. As a next step, the methods developed so far will be further refined and connected with each other in order to obtain a methodology allowing for a real-time prediction of possible and safe rescue routes in case of fire within standardized public buildings. Additionally, selected small-scale experiments will be used to validate the (fluid) mechanical models.

ACKNOWLEDGEMENT

This paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project KIBIDZ – *Intelligente Brandgefahrenanalyse für Gebäude und Schutz der Rettungskräfte durch Künstliche Intelligenz und Digitale Brandgebäudezwillinge*].

REFERENCES

[1] Modern Building Alliance, "EU fire safety guide," Brussels, 2019.

[2] J. Milke, V. Kodur and C. Marrion, "Overview of Fire Protection in Buildings, Federal Emergency Management Agency," Federal Emergency Management Agency (FEMA), 2002.

[3] K. B. McGrattan, R. J. McDermott, C. G. Weinschenk and G. P. Forney, "Fire Dynamics Simulator, Technical Reference Guide," National Institute of Standards and Technology, 2013.

[4] R. G. Rehm and H. R. Baum, "The Equations of Motion for Thermally Driven, Buoyant Flows," *JOURNAL OF RESEARCH of the Notional Bureau of Standards,* vol. 83, no. 3, pp. 297-308, 1978.

[5] D. Gawin, F. Pesavento and B. Schrefler, "Modelling of hygro-thermal behaviour of concrete at high temperature with thermo-chemical and mechanical material degradation," *Computer Methods in Applied Mechanics and Engineering,* vol. 192, no. 13-14, pp. 1731-1771, 2003.

[6] Deutsche Institut für Normung e.V., *DIN EN 1991-1-2, Eurocode 1: Einwirkungen auf Tragwerke - Teil 1-2: Allgemeine Einwirkungen - Brandeinwirkungen auf Tragwerke,* 2021.

[7] D. Dauti, A combined experimental and numerical approach to spalling of high-performance concrete due to fire, Grenoble, 2018.

[8] U. Starossek, Progressive collapse of structures, London: Telford, 2009.

[9] B. R. Ellingwood, R. Smilowitz, D. O. Dusenberry, D. Duthinh, H. S. Lew and N. J. Carino, "Best Practices for Reducing the Potential for Progressive Collapse in Buildings," National Insitut of Standards and Technology, Gaithersburg, 2007.

[10] A. Usmani, J. Rotter, S. Lamont and M. Gillie, "Fundamental principles of structural behaviour under thermal effects," *Fire Safety Journal,* vol. 36, no. 8, pp. 721-744, 2001.

[11] A. Sanad, S. Lamont, A. Usmani and J. Rotter, "Structural behaviour in fire compartment under different heating regimes," *Fire Safety Journal,* vol. 35, no. 2, pp. 99-116, 2000.

[12] F. Kiakojouri, V. De Biagi, B. Chiaia and M. R. Sheidaiia, "Progressive collapse of framed building structures: Current knowledge and future prospects," *Engineering Structures,* vol. 206, no. 110061, 2020.

[13] X. Guo, W. Li and F. Iorio, "Convolutional Neural Networks for Steady Flow Approximation," in *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, San Francisco, 2016.

[14] A. Liebert, W. Weber, S. Reif, B. Zimmering and O. Niggemann, "Anomaly Detection with Autoencoders as a Tool for Detecting Sensor Malfunctions," in *IEEE 5th International Conference on Industrial Cyber-Physical Systems (ICPS)*, Coventry, 2022.

[15] F. Aldakheel, R. Satari and P. Wriggers, "Feed-Forward Neural Networks for Failure Mechanics Problems," *MDPI Applied Sciences,* vol. 11, no. 6483, 2021.

Design Concept and Model-based Evaluation of an Exoskeleton for Low Back Support during Lifting Tasks

Daniel Greve*, Christian Kreischer
Elektrische Maschinen und Antriebssysteme
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
*greved@hsu-hh.de

Tim Schubert*, Robert Weidner
Laboratorium Fertigungstechnik
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
*tim.schubert@hsu-hh.de

***Abstract* – Workers in various context are exposed to physical stress during repetitive movements carrying heavy loads, resulting in musculoskeletal disorders like low back pain and lumbar disc herniation. Furthermore, consequences are direct and indirect costs due to rehabilitation and a high amount of days of absent. To counteract the physical workload, support systems like exoskeletons are developed for different settings like transferring patients in care. Nevertheless, positive and negative biomechanical effects of exoskeletons to the human body are not comprehensively examined and need to be evaluated by using different methods like simulation and modelling of the human-system interaction.**

This paper describes the process of development of a back support exoskeleton for the example of nursing care regarding context-based requirements, design concept and evaluation of the aimed biomechanical effects. In order to systematically evaluate the design, a combined model of human and exoskeleton is developed. Focusing on drive technology, dimensioning quantities are derived from the combined model. Further, an outlook on the analysis of effects of the design on stress to the human body is provided.

Keyword – Exoskeleton, Development Process, User-centered Design, Nursery Care, Modeling, Biomechanics

I. INTRODUCTION

Due to ongoing technological advances and other general needs (e.g., demographic changes), physical support systems such as exoskeletons are becoming increasingly popular [1]. In recent years, numerous exoskeletons have been developed to support different body regions and functions of the human body in various applications [2]. Examples include exoskeletons for supporting overhead work (e.g., [3], [4]) and walking e.g., [5]), and hand exoskeletons (e.g., [6]). In the medical field, such systems are often used for prevention and rehabilitation of upper and lower limb impairments [7]. They are used, for example, to enable a wearer to relearn movements by prescribing movements through an exoskeleton, e.g., as a result of a stroke or accident [8]. Support systems are also used to compensate for the loss of muscle strength for people who can no longer access their full muscle strength due to age or illness. For industrial, nursing care or military purposes, exoskeletons are used to prevent musculoskeletal disorders due to the overuse of muscles and joints in repetitive physically demanding tasks, as well as to extend the wearer's capabilities such as lifting and transporting heavy loads [9], [10].

Exoskeletons are diverse in their function and design. Depending of the intention of use, the user movement can be e.g. stabilized, expanded, supported, strengthened or facilitated. Basically, exoskeletons can be classified differently. This is often done with regard to the support areas (e.g., back and shoulder). Of greater technical relevance is, on the one hand, the morphological structure (type and manner of force transmission, in which biomechanically equivalent structures and end effector structures are to be fundamentally distinguished) inclusively the rigidity of the force transmitting structure (differentiation between soft and hard structures or structures with and without compliance/flexibility) as well as on the other hand the kind of support and functionalities (context-based characteristics of support). Depending on the approach and application purpose, different actuator technology, sensor technology and interfaces (for operation and force transmission) are also used. Today's market-ready products use rotating or linear actuators that transmit forces to humans via appropriate mechanics. Electric, pneumatic or hydraulic actuators are used [9]. Textile systems use stretch or similar structural elements.

In the project "Intelligente Auslegung und Optimierung von KI basierten, physischen (Körper-) Unterstützungssystemen mit moderner Antriebstechnologie" (KIKU), founded by dtec.bw, the purpose is to design a back support system for caregivers based on an electric drive, which is optimized and built using intelligent model-based methods. These methods can be applied to the design of the system, taking into account electromagnetic and mechanical system properties. Hence, intelligent algorithms efficiently optimize extensive multi-physical models. Optimization goals are, for example, the selection of the best possible number and design of drive units acting in parallel and their arrangement in relation to each other in the overall system.

To be able to validate models for later optimization, a demonstrator platform for a lower back exoskeleton is developed. The development process, without extensive use of

https://doi.org/10.24405/14554

models, is described in section II. Further, a modeling approach is presented in section III and applied to the lower body exoskeleton in section IV.

II. Practice-oriented developtment of Lower Body Exoskeleton

A. *Motivation*

Caregivers and nurses are confronted by a variety of mental and physical workplace exposures [11]. The day of care workers is characterised by a high demand of social interaction with patients within time pressure and physical strain resulting from long time standing, lifting and transferring patients. Therefore, they are exposed by a high strain of the musculoskeletal system resulting in muscular disorders in shoulder and neck and low back pain (LBP) [12]. Because of risk factor like many working hours, repetitive lifting tasks, trunk flexion and rotation, LBP is common in 37 % of caregivers [13]. Besides physical disorders, negative consequences are also direct costs for rehabilitation and physical therapy and indirect costs during days of absence and lower productivity. Additionally, the demographic change lead to higher demand for nurses and caregivers. Good working conditions are needed to maintain healthiness until retirement within the care setting.

To avoid high strain in spine and lumbar load on intervertebral disks, professional caregivers learn "spine-friendly" lifting techniques in trainings and educations [14]. Nevertheless, there is poor evidence regarding the efficacy for these interventions in preventing low back pain [15]. Therefore, physical support is crucial to lower heavy strain. There are several approaches including lifting aids like ceiling-based patient lifts, sliding boards or body worn devices called exoskeletons. These assistive devices can help to ease physical demanding and high intensity work. Not least because of the social interaction between nurses and patient, the purpose is not to substitute human work, but to support the user while doing his work.

Exoskeletons can be used early in "working life" as a primary prevention to avoid the incidence of physical complaints due to heavy load. Kermavnar et al. [16] reported a reduction in back muscle activity and spinal compression forces, which could lead to a reduction of LBP. Because exoskeletons are relatively new on the market and LBP is already present in many caregivers, they may also help to prevent a worsen of existing disorders in terms of the secondary prevention.

There are several systems already developed to assist lifting tasks and support the back muscles [17], but not all of them are appropriate to apply them into care setting. Because there are no specific developed exoskeletons for nurses or caregivers regarding there special needs, we evaluate the Scoot Pivot Transfer [18] as one of the crucial lifting techniques for patients using motion capture and electromyography to derive requirements for exoskeleton development.

B. *Biomechanical Analyses of Lifting Tasks in Nursery Care*

In order to evaluate the requirements, which are given by the lifting tasks in care setting, we conducted a preliminary experiment using motion capture and electromyography. To measure the kinematics during the lifting tasks, a mobile Xsens MTw Awinda System was used (Xsens Technologies BV, Enschede, Netherlands). With a Myon 320 system (myon AG, 275 Schwarzenberg, Swiss), the muscle activity of the m. erector spinae was recorded and scaled relatively to the maximum voluntary contraction (MVC). The ergonomic evaluation tool Industrial Athlete (IA, scalefit) was used to estimate the lumbar disc compression of L5-S1 during lifting.

We present the upper body flexion angle in comparison to the muscle activation of m. erector spinae when performing the Scoot Pivot Transfer.

The Scoot Pivot Transfer is a typical method to move patients from the bed into a wheelchair and is depicted in Figure 1, whereby the first three picture show the movement cycle. The kinematic flexion angle during the transfer is shown in the first diagram. The second diagram presents the muscle activation of the low back muscle (m. erector spinae). The last curve displayed the compression force of the lumbar spine.

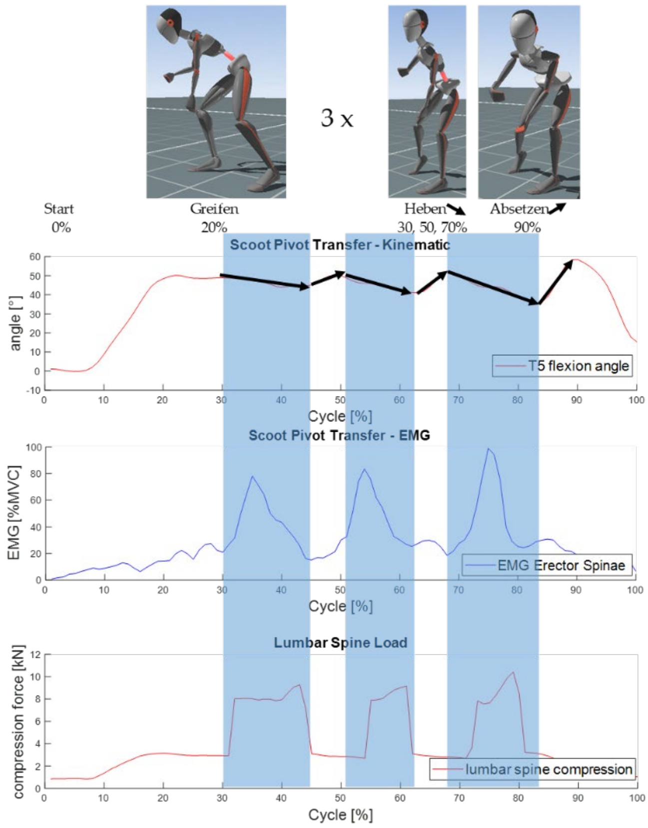


Figure 1: Scoot Pivot Transfer and analysis of joint angle (T5), electromyography and lumbar spine compression.

The transfer technique can be divided into three phases. During Phase 1, the caregiver holds the patient around the back with the right hand and at the thigh with the other hand. When holding the patient safety, the caregiver lifts the person in phase 2, moves him a small distance to the side by squatting and rotating and sets him down. This phase is repeated three times to increase the moved distance. At phase 3, the patient is set down into his wheelchair.

As can be seen, the physical strain onto the lower back rises sharply when lifting the patient. The muscle activation peaks around 80 % of the maximal voluntary contraction and the compression force of the lumbar disc amounts up to 10 kN. The exoskeleton to be developed is intended to reduce the maximum load to the body. The blue box plots show the periods, where the device must actively support the user during the task.

This experiment allows insights about the requirements, the exoskeleton has to fulfil regarding the mechanical structure, the actuator and control algorithm. Therefore, an actuator with high acceleration and torque is needed, due to the fast slope of muscular and tissue stress when lifting the patient. It needs to be activated three times during 15 % of the whole lifting cycle, which lasts about 10 seconds. The control unit must ensure the real-time requirements to make sure a timely actuation.

A more detailed analyses of requirements to be considered for the design of exoskeletons are given below.

C. Requirements

To the best of our knowledge, there are only two specific developed exoskeletons for nurses [10, 19]. Most devices were developed for back support during unspecific lifting tasks and where also tested in laboratory with healthy subjects [16], [2]. Nevertheless, there are different preferences and characteristics, that are beneficial for a medical setting when working with patients in comparison to an industrial setting.

The exoskeleton needs to be designed regarding to general requirements for human-system interactions, as well as to specific requirements, that are given in order to the context of nursery care and for the work with patients. Besides the mechanical design, properties like acceptance, wearing comfort and safety are essential for design optimization. Some important characteristics are shown afterwards in detail.

The **purpose/function** of the exoskeleton is to support care workers during lifting and transferring patients. Regarding the stress to the lumbar spine, it has to reduce load by actively assist the degree of freedom of hip and upper body extension during static posture and movements.

The system is supposed to ensure the users **kinematic** conditions by mimicking the user movements in ways, that he is able to move freely without any restrictions when wearing the exoskeleton. It has to be verified, that no compensatory movements are made when using the exoskeleton, in order to accomplish tasks that are not feasible in an "natural" manner.

Safety is elementary to consider and has to be observed from two perspectives. One for the user itself, and the other regarding to the patients, who are also in direct or indirect contact with the device. Therefore, hardware security elements like an emergency stop button and software control algorithms that continuously record data in order to stop the device at adverse events are required to ensure safety. This includes mechanical restrictions, to not exceed any intended ranges of motion. As the patients are in contact with the device, it must be ensured, that he is not able to grasp into the system and get bruises or any else injuries.

The **control** unit, usually a microcontroller or –computer, uses input sensor information like force from Force Sensing Resistors (FSR) and joint angles, speed or acceleration from Inertial Measurement Units (IMU). Based on this information, the control algorithm operates the actuation system and activate or deactivate the supporting function dependent to the user motion and intention. For this, the user should always retain sovereignty over the system, without becoming externally determined. This is done by a feedback mechanism with ongoing target-performance comparison. Nevertheless, the major challenge and current research in the field of human-system interaction is to predict the intentions of the users prior to the movement, to assure a fast system acting in real time.

The **actuation** module generates the external force in order to support the users lifting task. Generally, there are several possible technologies like electro motors, pneumatic, hybrid or hydraulic actuators [20]. Special drive technologies like artificial polymer muscle fibers [21] or tubular linear motors [22] may be used in exoskeletons. Every drive system has its own advantages and disadvantages, expressing e.g. in power to weight ratio, dynamics, heat generation, efficiency or power consumption.

Acceptance is one of the most crucial requirements when developing system for human users, because a perfectly working device is nothing worth, if it is not used. Therefore, subjective determinants should be considered for the design process by integrating users into the development as soon as possible. To enhance the acceptance of an exoskeleton for the non-industrial context, the design should be ideally invisible and wearable under working clothes. Moreover, the system should be put on quick and easy, because of the time pressure during work. Major demands are made regarding the wearing comfort, as it has to be worn during the working day without disturbing the user while doing his working routine.

Wearing comfort referring to the human-system interfaces. They have two inherent functions: (1) transfer forces to the body and (2) ensure the greatest possible comfort. Whereas the material for the first function is supposed to be stiff in the direction of force, it needs to be soft and flexible vertical to the body to avoid pressure peaks at the contact area and therefore facilitate a comfortable wear throughout the use of the exoskeleton. Moreover, regulation of heat and humidity needs to be considered, as well as the weight and the geometry of the system, as it should be designed lightweight and near the body without overhanging structures. That includes the positioning of the major weight near the centre of the body.

An easy **handling and usability** include a short time in taking the system on and off without any help. Regarding the adaptability to different users, the exoskeleton has to be adjusted to fit the anthropometries of the user and needs to be adjusted to guarantee the alignment of body and system joints. A user control panel is mandatory to switch on/off and to regulate the required supporting force. The entirety adjustment functions should be characterized by their simplicity and intuition in use.

The **compatibility** of the supporting device is necessary due to the setting of nursery care. Therefore, it has to be compatible to the working clothes, environment and equipment. A protection class of minimum IP44 is obligatory in order to protect users and surrounded persons from the drive system or other moving parts.

Maintenance is preferred as low as possible. Nevertheless, with daily use, wear and defective parts are not completely unavoidable. An easy repair can be provided by a modular system with interchangeable parts.

The **adaptability** to individual and context specific requirements must be taken into account. Therefore, a software based differentiation of various contexts like dynamic tasks when lifting patients or static demands resulting from holding and walking with the patient must be distinguished. Moreover, adjustment to the magnitude of supporting force must be enabled e.g. with a rotary knob to fulfil individual demands for physical relief.

D. Design Concept

Exoskeletons are usually distinguished regarding the materials used for the structure in rigid exoskeleton and soft exosuits. Whereas rigid devices are primary made out of material with high stiffness like metal and carbon, soft exosuits comprises mostly fabrics and flexible plastics. Due to the utilized material, the advantages of exosuits are a comfortable and lightweight wear, while rigid systems beneficial in transferring higher loads by simultaneous redirecting compression forces from body into the system. In contrast, textiles are suitable only to transfer tensile forces but no compression forces, which could lead to additional strain to joints and passive body tissue like discs and cartilage. Regarding the mechanical and kinematic structure of rigid systems, the movements are primary possible at the predefined joints of the system, whereas soft exosuits allows more wide-ranging degrees of freedom without restricting user movements. Nevertheless, the goal is to combine the advantages of both types into a hybrid exoskeleton with high wearing comfort due to soft fabrics at the body-system interfaces as well as lightweight and stiff material to transfer forces without harmful effects to the body.

A second distinctive feature between exoskeletal systems are the used elements for actuation. An active device (powered) uses actuation modules like electric motors, pneumatic cylinders or linear actuators with additional energy source and controlling unit. Contradicting, passive devices (unpowered) uses elastic materials like rubber band or springs, which are storing energy that is introduces by the user during preceding movements. Due to the fixed torque profile, it is not possible to vary the given support regarding different needs like various lifting techniques or strain magnitudes resulting from different load weight. Moreover, there is no automatic deactivation when supporting torque is not intended like bending forward without extern stress or for ancillary tasks.

The fundamental design concept of our exoskeleton is an actively controlled system that should comprises the advantages of soft and rigid structures. It is characterized by four main modules of the basic structure and the involved drive system and sensors (see FIGURE 2).

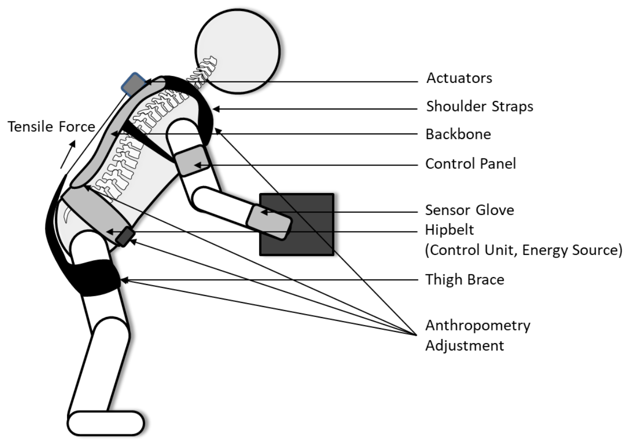


FIGURE 2. CONCEPT OF EXOSKELETON STRUCTURE.

The exoskeleton is built likewise a backpack. The **shoulder straps** act as human-system and system-system interface. They transmit the force to the upper body due to high stiffness in direction of force by simultaneously cushion the forces vertical to the body to maintain high wearing comfort. Additionally, the actuators and a backbone force transmitting structure are connected with the straps.

An artificial **backbone** made of aluminum is connected between the shoulder straps and a hip belt to transmit the supporting force parallel to the human spine. The backbone is flexible in direction of flexion and extension but does not allow compression upright to the spine. It is important to redirect forces that are not acting in the direction of the intended assisted degrees of freedom to avoid additional compressive forces to joints and lumbar discs.

In equivalence of the shoulder straps, the **hipbelt** is connected with the end of the backbone and transmit forces like a backpack onto the hip bones. Furthermore, an interface guides a steel cable that transmit the force from the actors at the upper back to the thighs. Small integrated pockets contain the energy source and the control unit. To make anthropometric adjustments, the shoulder straps, backbone and hipbelt comprise corresponding elements.

To generate a hip joint moment, the force is applied to a **thigh brace** around the left and right leg. A moment arm of approximate 0.1 m is built by the distance from the hip center of rotation to the point where the brace makes contact to the posterior waist [23].

In addition to the basic structure, an **actuation** module actively actuate the exoskeleton by two electrical EC-Motors, where a steel cable is connected to a pulley. An IMU **Sensor** Net determine the body postures to deliver input signals for the control unit to activate the drive system in order to support the upper body extension during lifting tasks. To recognize the load when grapping a patient, a **glove** with integrated pressure sensors is planned as an auxiliary to improve the control algorithm through the input signals.

III. MODELLING CONCEPT

Modelling is conducted with the goal to develop insights in influences on the function of the lower back exoskeleton. Eventually, a mathematical approach can lead to an integrated design methodology where relevant influences and dependencies of, e.g., the control law and the drive system can be optimized in an early phase of product development.

The interaction between human and exoskeleton is modeled as differential algebraic equation. A combined model, comprising of a human multibody model, an exoskeleton multibody model and an electromagnetic drive system model is suggested. The combined model is depicted in FIGURE 3. As can be seen, the human multibody model consists of rigid bodies, called body segments. They are connected by ball joints and are arranged in a tree structure. The root joint is at the hip body segment, which is highlighted in FIGURE 3.

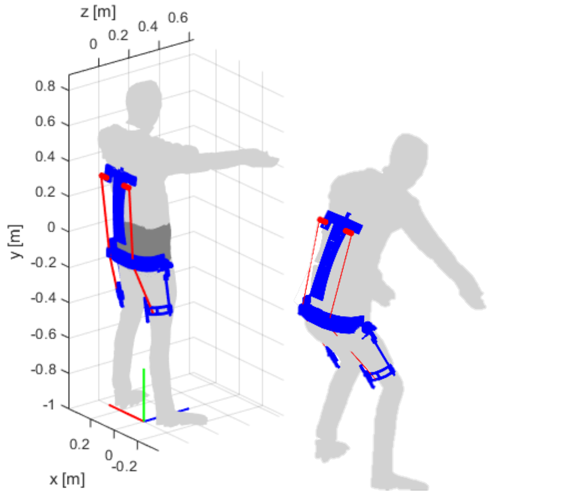


FIGURE 3: COMBINED MODEL IN FINAL (LEFT) AND INITIAL (RIGHT) POSE.

In the following, the equations for this model are mostly presented without extensive explanation. Relevant topics in multibody modeling are reviewed in [24]. The derivation of the human multibody model from 3D body scans is presented in [25]. For modelling of electromagnetic actuators, it is referred to [26] and [28]. The combined model comprises of the equations

$$\begin{bmatrix} M_{hum}(q_{hum}) & 0 \\ 0 & M_{exo}(q_{exo}) \end{bmatrix} \begin{bmatrix} \ddot{q}_{hum} \\ \ddot{q}_{exo} \end{bmatrix} + \begin{bmatrix} k_{hum}(q_{hum}, \dot{q}_{hum}) \\ k_{exo}(q_{exo}, \dot{q}_{exo}) \end{bmatrix} - C^T \lambda = \begin{bmatrix} g_{hum}(q_{hum}) \\ g_{exo}(q_{exo}) \end{bmatrix} + \begin{bmatrix} \tau_{hum} \\ \tau_{exo} \end{bmatrix} \tag{1}$$

$$c(q_{hum}, q_{exo}) = 0 \tag{2}$$

$$C = \frac{\partial c}{\partial q} \tag{3}$$

$$\tau_{exo}^T = \begin{bmatrix} 0 & .. & \frac{\partial \Psi_{m,j}^T}{\partial q_{drive,j}} i_j & .. \end{bmatrix} \tag{4}$$

where (1) represents the multibody dynamics, (2) and (3) the coupling constraints that are necessary to join both multibody models and (4) the electromagnetic torque production.

In the equations, indices hum and exo stand for human resp. exoskeleton, M represents a mass matrix, k a vector for centrifugal and Coriolis forces, g a vector for gravitational forces, τ a vector for control forces and torques and q a vector for generalized coordinates. Further, c represents coupling constraints and λ a vector of Lagrange multipliers that enforce the coupling in equation (1) and represent interaction forces. The column vector $\Psi_{m,j}$ represents the flux linkage due to permanent magnet excitation, column vector i_j the current in each strand and $q_{drive,j}$ is the generalized coordinate of the rotor of electric drive j. As the electric drives are part of the exoskeleton, the generalized coordinate $q_{drive,j}$ is part of the vector for exoskeleton generalized coordinates q_{exo}.

For model-based analysis of the human system interaction, it is assumed that human generalized coordinates q_{hum} differ only negligibly with and without exoskeleton. This reflects the goal to minimally restrict human motion. With this assumption, inverse dynamics of the combined model, i.e. determination of human control torques τ_{hum} can be performed on tracking data gathered with unapplied exoskeleton. Hence, the interaction of human and exoskeleton is primarily evaluated regarding human control torques τ_{hum}.

A. *Exoskeleton Drive System Model*

As the drive system is regarded in particular, modelling of it is introduced more thoroughly. Each electric drive is able to generate the generalized force

$$\tau_{drive,j} = \left(\frac{\partial \Psi_{m,j}^T}{\partial q_{drive,j}} \right) i_j. \tag{5}$$

As shown in equation (5), the current-force relation of the drive system is modeled. The vector of flux linkages due to permanent magnet excitation is

$$\Psi_{m,j}^T = \hat{\Psi}_{m,j} \begin{bmatrix} cos(p_j a_j) & cos(p_j b_j) & cos(p_j c_j) \end{bmatrix} \tag{6}$$

$$a_j = q_{drive,j}, b_j = q_{drive,j} - \frac{2\pi}{3}, c_j = q_{drive,j} + \frac{2\pi}{3} \tag{7}$$

where p_j is the number of pole pairs of the electric drive j and $\hat{\Psi}_{m,j}$ is the fundamental amplitude flux linkage due to permanent magnet excitation. The dynamic system from voltages to current is not regarded at this point. Further note, that with this model only permanent magnet synchronous machines with three phases and without reluctance, ripple torque and iron saturation can be modeled.

For a given drive torque $\tau_{drive,j}$, the choice of strand current vector i_j is ambiguously. To reproduce reality adequately, it is leaned on the commonly used procedure of field oriented control [26], [27]. A transformation is applied on equation (5), such that

$$\tau_{drive,j} = \left(\frac{\partial \tilde{\Psi}_{m,j}^T}{\partial q_{drive,j}} \right) i_{dq0,j} \tag{8}$$

$$\frac{\tilde{\Psi}_{m,j}^T}{\partial q_{drive,j}} = \left(\frac{\partial \Psi_{m,j}^T}{\partial q_{drive,j}} \right) K^{-1} = \begin{bmatrix} 0 & \hat{\Psi}_{m,j} p_j & 0 \end{bmatrix} \tag{9}$$

$$K^{-1} = \begin{bmatrix} cos(p_j a_j) & -sin(p_j a_j) & 1 \\ cos(p_j b_j) & -sin(p_j b_j) & 1 \\ cos(p_j c_j) & -sin(p_j c_j) & 1 \end{bmatrix} \tag{10}$$

with $i_{dq0,j}$ as the transformed current vector. It can be seen easily, that the torque $\tau_{drive,j}$ only depends on the second component $i_{q,j}$ of the transformed current vector. Hence, in practice, strand currents i_j are chosen such that only $i_{q,j}$ is created. A mapping from drive torque $\tau_{drive,j}$ to strand currents i_j can now be established as,

$$i_j^T(\tau_{drive,j}) = -\begin{bmatrix} sin(p_j a_j) & sin(p_j b_j) & sin(p_j c_j) \end{bmatrix} \sqrt{2} \hat{\imath}_{drive,j} \tag{11}$$

$$\hat{\imath}_{drive,j} = \frac{\tau_{drive,j}}{\sqrt{2} \hat{\Psi}_{m,j} p_j} \tag{12}$$

where $\hat{\imath}_{drive,j}$ is the effective current amplitude of electric drive j.

B. *Static model*

Derivation of equations (1) to (4) in symbolic form appears to be burdensome. To be able to gain insight in the system behavior in a simple way, a static model is derived preliminary. In the model equations (1) to (4), equation (1) is substituted with

$$-C^T\lambda = \begin{bmatrix}\tau_{hum}\\ \tau_{exo}\end{bmatrix} \tag{13}$$

while the other equations remain the same.

This model covers the relation from drive currents in the exoskeleton i_j to torques in the human body τ_{hum} under neglection of dynamic influences, e.g. inertia of the drive system. As no derivatives appear in these equations, it is purely algebraic.

To solve the static model equations (13) and (2) - (4) for the human control torques τ_{hum} with a given trajectory of human generalized coordinates q_{hum} and drive currents i_j, it is required to solve equation (2) for exoskeleton generalized coordinates q_{exo}. Subsequently, equation (13) is solved for Lagrange multipliers λ and human control torques τ_{hum}.

IV. Model-Based Evaluation

In the following, the static model is applied to analyze the effects of a given control law for the generalized control forces on the exoskeleton, i.e.

$$\tau_{drive,1} = \tau_{drive,2} = -0.035\, sin(q_{hum,7}). \tag{14}$$

The trajectory for human generalized coordinates q_{hum} is generated artificially. Both start (lower) and end pose (raised) are depicted in Figure 3. In future applications, it will be gathered from motion tracking. The component $q_{\mathrm{hum},7}$ refers to the rotation of the hips body segment around the x-axis.

The fundamental amplitude flux linkage due to permanent magnets $\widehat{\Psi}_{\mathrm{m},j}$ is taken from the data sheet of the preliminary applied drive system (Maxon EC-4 Pole 22 24V with Maxon GP22 HP 62:1, Maxon Motor AG, Sachseln, Switzerland). Further, kinematic relations for the exoskeleton are known from manufacturing data.

It is shown exemplarily, how the combined model allows the derivation of dimensioning quantities for the electric drive system. Further, a first approach for the analysis of the human system interaction is presented. Hence, first steps towards an integrated design methodology are demonstrated.

Firstly, trajectories for actuator rotor generalized coordinates $q_{\mathrm{drive},j}$ can be derived. Numerical differentiation with respect to time yields the rotational speeds $\dot{q}_{\mathrm{drive},j}$, which is a relevant dimensioning quantity. Further, drive system modelling allows the calculation of drive currents i_j resp. their effective amplitude $\hat{\imath}_{\mathrm{drive},j}$. Speed and current quantities are plotted over time for electric drive 1 in Figure 4. These results indicate that the drive system was chosen correctly, such that it can operate within its specified limits.

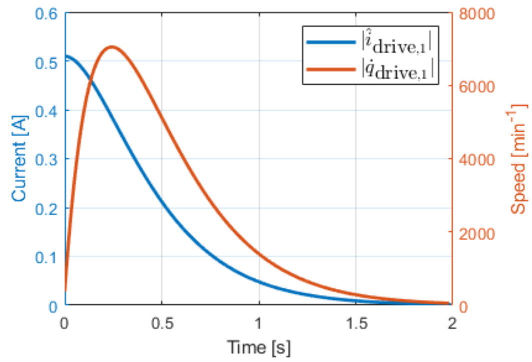


Figure 4: Electric Drive Current and Speed from static model.

Another goal is the estimation of influences on the human. In a first approach, human control torques $\boldsymbol{\tau}_{\mathrm{hum}}$ are considered for this estimation. In context of the static model, they ensure balance of momentum and hence represent the influence of the exoskeleton. In Figure 5, trajectories for human control torques are presented.

Human control torques around local x-axes for the right and left hip-upper leg joint $\tau_{\mathrm{hum},43}$ resp. $\tau_{\mathrm{hum},52}$ are regarded. Further, human control torque around global x-axis for the root-hip joint $\tau_{\mathrm{hum},4}$ is regarded.

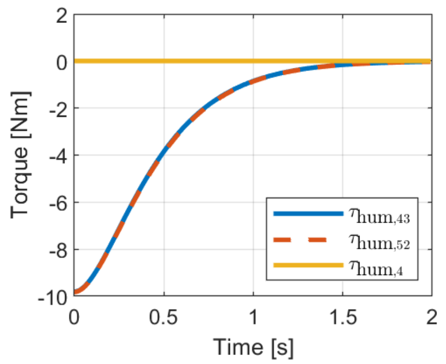


Figure 5: Human Control Torques Due to Exoskeleton.

Regarding the control torques $\tau_{\mathrm{hum},43}$ resp. $\tau_{\mathrm{hum},52}$, the results indicate a support torque of approx. -10 Nm that decreases with time. Surprisingly, the control torque $\tau_{\mathrm{hum},4}$ is zero. The reason for this is the model structure. As described in Section III, the human multibody model consists of a tree structure, beginning at the hips segment. This renders the forces and torques from the lower part of the exoskeleton to cancel the forces and torques from the upper parts of the exoskeleton in the hips segment. To circumvent this, additional bearing loads b are introduced at the feet. Thus, equation (*13*) is modified again to

$$-C^T\lambda = \begin{bmatrix}\tilde{\tau}_{\mathrm{hum}}\\ \tilde{\tau}_{\mathrm{exo}}\end{bmatrix} + b. \tag{15}$$

Bearing loads b are chosen such that they cancel the control torques $\tau_{\mathrm{hum},43}$ and $\tau_{\mathrm{hum},52}$. Hence, forces and torques from the lower part of the exoskeleton are now transmitted to the feet and canceled by corresponding bearing loads. In Figure 6, a trajectory for control torque $\tilde{\tau}_{\mathrm{hum},4}$ is presented. In case of introduced bearing loads, a support torque for the hips body segment of approx. 17 Nm, decreasing with time is observed.

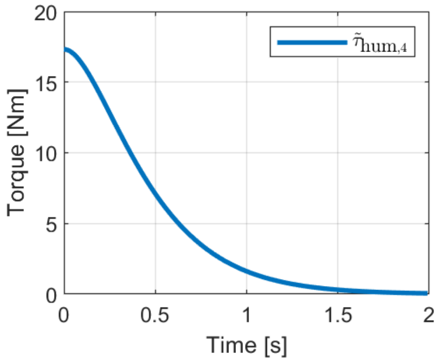


FIGURE 6: QUANTIFICATION OF EXOSKELETON EFFECTS.

The static model does not cover any influences of human masses and inertias. Thus, with this model, it is not possible to find a relation between the load inside the human body during a movement and its reduction due to the exoskeleton. As already mentioned, it is at this point aimed at demonstrating an approach for an integrated design rather than conducting a complete dimensioning.

V. CONCLUSION

This paper provides an overview of the current course of the dtec.bw project KIKU. The approach to develop a hybrid exoskeleton for back support in the setting of nursing care was given. To address the special requirements of care workers, including prevalent tasks like different patient lifting techniques, a preliminary experiment demonstrate the feasibility of biomechanical assessment using measurement devices for three-dimensional kinematic and electromyography analyses. As an example, the Scoot Pivot Transfer Technique shows a high demand of muscle activation and spine compression force up to 80 % MVC and 10 kN, respectively. During working routine and repetitive lifting tasks, this may lead to high stress to the musculoskeletal system, resulting in low back pain and disorders like lumbar disc herniation. To lower the physical strain during lifting tasks, an active driven exoskeleton will be developed by using rigid materials to transmit forces and soft textiles to maintain a high wearing comfort. As first step, a concept design was made, that depicts the main structure of the system including crucial elements of human-system and system-system interfaces, as well as the actuation module and the envisioned path of force. Further, an approach for an integrated design methodology, focusing on drive technology was presented. With a combined model of human, exoskeleton and exoskeleton drive system it is possible to evaluate the requirements of individual motion on dimensioning quantities (e.g. rotational speed) of the drive system. For an exemplary motion, it can be seen, that the requirements are fulfilled by the preliminary selected drive system. Lastly, an outlook on the model-based analysis of human system interaction was explained.

The next step is the construction of a first prototype of the concept design, taking into account requirements such as kinematics, usability, safety or wearing comfort to achieve a high level of acceptance. The physical effects of the exoskeleton on the body will be examined using similar biomechanical methods that has been presented.

ACKNOLODGEMENT

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [KIKU]. The content has been originated by the authors and reflect the current course of the project.

REFERENCES

[1] R. B. R. &. Statista, „Absatz* von Exoskeletten weltweit in den Jahren von 2015 bis 2025,“ 21 Dezember 2016. [Online]. Available: https://de.statista.com/statistik/daten/studie/796472/umfrage/absatz-von-exoskeletten-weltweit/. [Zugriff am 25 August 2022].

[2] R. Weidner, C. Linnenberg, N. Hoffmann, G. Prokop und V. Edwards, „Exoskelette für den industriellen Kontext: Systematisches Review und Klassifikation,“ in *GfA, Frühjahrskongress 2020*, Berlin, 2020.

[3] C. Ishiii, H. Yamamoto und D. Takigawa, „Development of a New Type of Lightweight Power Assist Suit for Transfer Work,“ in *Asia-Pacific Conference on Computer Aided System Engineering*, Piscataway, 2015.

[4] I. Pacifico, A. Scano, E. Guanziroli, M. Moise, L. Morelli, A. Chiavenna, D. Romo, S. Spada, G. Colombina, F. Molteni, F. Giovacchini, N. Vitiello und S. Crea, „An Experimental Evaluation of the Proto-MATE: A Novel Ergonomic Upper-Limb Exoskeleton to Reduce Workers' Physical Strain,“ *IEEE Robotics and Automation Magazine,* Bd. 27, Nr. 1, p. 54–65, 2020.

[5] G. Lv, H. Zhu und R. D. Gregg, „On the Design and Control of Highly Backdrivable Lower-Limb Exoskeletons: A Discussion of Past and Ongoing Work,“ *IEEE control systems,* Bd. 38, Nr. 6, p. 88–113, 2018.

[6] Z. Yao, R. Weidner, C. Lineberg, A. Wollesen und J. Wulfsberg, „Gestaltung eines biomimetischen, weichen Muskelhandschuhs,“ in *Technische Unterstützungssysteme, die die Menschen wirklich wollen*, Hamburg, Laboratorium Fertigungstechnik, Helmut-Schmidt-Universität, 2016.

[7] A. Plaza, M. Hernandez, G. Puyuelo, E. Garces und E. Garcia, „Lower-limb medical and rehabilitation exoskeletons: A review of the current designs,“ *IEEE Reviews in Biomedical Engineering,* 7 Mai 2021.

[8] E. Blume, „Von Exoskeletten und Servicerobotern – die Rehabilitation der Zukunft,“ 2019. [Online]. Available: https://www.medica.de/de/News/Thema_des_Monats/Ältere_Themen_des_Monats/Themen_des_Monats_2019/Robotik_in_der_Rehabilitation. [Zugriff am 15 8 2022].

[9] M. P. Looze, T. Bosch, F. Krause, K. S. Stadler und L. W. O'Sullivan, „Exoskeletons for industrial application and their potential effects on physical work load,“ *Ergonomics,* Bd. 59, Nr. 5, p. 671–681, 2016.

[10] Y. Hasegawa, T. Hoshino und A. Tsukahara, „Wearable assistive device for physical load reduction of caregiver

- adaptive to caregiver's motion during transferring support,“ IEEE, p. 1–6.

[11] R. Jang, W. Karwowski, P. M. Quesada, D. Rodrick, B. Sherehiy und S. N. Cronin, „Biomechanical evaluation of nursing tasks in a hospital setting,“ *Ergonomics,* 30 Oktober 2007.

[12] K. G. Davis und S. E. Kotowski, „Prevalence of Musculoskeletal Disorders for Nurses in Hospitals, Long-Term Care Facilities, and Home Health Care: A Comprehensive Review,“ *Human factors,* Bd. 57, Nr. 5, p. 754–792, 2015.

[13] AOK-Bundesverband, Hrsg., Betriebliche Gesundheitsförderung in der Pflege, Berlin: KomPart, 2021.

[14] E. L. Peterson, J. D. McGlothlin und C. L. Blue, „The development of an ergonomics training program to identify, evaluate, and control musculoskeletal disorders among nursing assistants at a state-run veterans' home,“ *Journal of occupational and environmental hygiene,* Bd. 1, Nr. 1, pp. D10-6, 2004.

[15] W. van Hoof, K. O'Sullivan, M. O'Keeffe, S. Verschueren, P. O'Sullivan und W. Dankaerts, „The efficacy of interventions for low back pain in nurses: A systematic review,“ *International journal of nursing studies,* Bd. 77, p. 222–231, 2018.

[16] T. Kermavnar, A. W. Vries, M. P. Looze und L. W. O'Sullivan, „Effects of industrial back-support exoskeletons on body loading and user experience: an updated systematic review,“ *Ergonomics,* Bd. 64, Nr. 6, p. 685–711, 2021.

[17] A. Ali, V. Fontanari, W. Schmoelz und S. Agrawal, „Systematic Review of Back-Support Exoskeletons and Soft Robotic Suits,“ *Frontiers in bioengineering and biotechnology,* 2 November 2021.

[18] J. Hess, L. Kincl und D. Mandeville, „Comparison of three single-person manual patient techniques for bed-to-wheelchair transfers,“ *Home healthcare nurse,* Oktober 2007.

[19] M. Tsuzura, T. Nakakuki und D. Misaki, „A mechanism design of waist power assist suit for a caregiver by using torsion springs,“ IEEE, 102013, p. 866–868.

[20] F. Hussain, R. Goecke und M. Mohammadian, „Exoskeleton robots for lower limb assistance: A review of materials, actuation, and manufacturing methods,“ *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of engineering in medicine,* Bd. 235, Nr. 12, p. 1375–1385, 2021.

[21] G. M. Spinks, „Stretchable artificial muscles from coiled polymer fibers,“ *Journal of Materials Research,* Bd. 31, Nr. 19, p. 2917–2927, 2016.

[22] F. Dreishing und C. Kreischer, „Optimization of Force-to-Weight-Ratio of Ironless Tubular Linear Motors Using an Analytical Field Calculation Approach,“ *IEEE Transactions on Magnetics,* p. 1, 2022.

[23] E. P. Lamers und K. E. Zelik, „Design, modeling, and demonstration of a new dual-mode back-assist exosuit with extension mechanism,“ *Wearable Technologies,* Bd. 2, 2021.

[24] R. Seifried, Dynamics of Underactuated Multibody Systems, Cham: Springer International Publishing, 2014.

[25] D. Greve, M. Tiator, C. Kreischer und C. Geiger, „Personalized Motion Analysis with Consideration of Body Segment Shapes,“ in *Mensch und Computer 2022 (MuC ’22)*, Darmstadt, 2022.

[26] P. C. Krause, O. Wasynczuk und S. D. Sudhoff, Analysis of Electric Machines, New York: Wiley, 2001.

[27] E. Bolte, Elektrische Maschinen, Berlin: Springer-Verlag GmbH, 2018.

Konzeption einer durchgängigen Prozesskette für die automatisierte Herstellung von Kompositbauteilen durch Faserablage

Pezhman Pourabdollah, Raphael Höfer, Alexander Fay
Institute of Automation
Helmut-Schmidt University, Hamburg, Germany
*pezhman.pourabdollah@hsu-hh.de

Henrik Eschen, Lennart Finger
CTC GmbH
Stade, Germany
*henrik.eschen@airbus.com

Kurzfassung **– Die Fertigung von Bauteilen aus Kompositen mittels automatisierter Faserablegeverfahren gewinnt in der heutigen Zeit zunehmend an Bedeutung. Grund hierfür sind unter anderem die steigenden Anforderungen an Gewichtseinsparungen sowie Reproduzierbarkeit und Zuverlässigkeit in der Produktion. In dieser Veröffentlichung werden die Prozessketten etablierter Ablegeverfahren dargestellt und im Hinblick auf Kompatibilität einzelner Prozessschritte erläutert. Ziel dieser Arbeit ist die Vorstellung eines Konzepts des AFP-Verfahrens zur Kontinuität der Prozesskette vom Design bis hin zum fertigen Bauteil.**

Keyword – Faserablage, Automatisierung, Industrie 4.0, Digitalisierung

I. Einleitung

In der heutigen Zeit gewinnen Bauteile aus faserverstärkten Verbundwerkstoffen in der Industrie - insbesondere in der Luftfahrt - zunehmend an Bedeutung. Die steigende Nachfrage nach Faserverbundwerkstoffen ist unter anderem auf ihre besonders guten Materialeigenschaften zurückzuführen und sind daher ein vielversprechendes Material für die Luftfahrt. Gemäß dem „State of the Industry Report 2020" von der American Composite Manufacturing Association (ACMA) ist das starke Wachstum in der Kohlefaserverbundindustrie einerseits durch die steigende Nachfrage am Material als auch auf die stetig steigenden Auslieferungen von Flugzeugen zurückzuführen [1]. Airbus prognostiziert in seinem aktuellen Global Market Forecast 2022 einen Anstieg der Passagier- und Frachtflugzeugflotte um rund 250% bis zum Jahr 2041. Trifft die Prognose ein, stehen der Luftfahrtbranche und damit auch Faserverbundwerkstoffen große Herausforderungen bevor [2].

Durch den Einsatz von Faserverbundwerkstoffen werden viele Vorteile im Gegensatz zu üblichen metallischen Werkstoffen erreicht. So kann durch ihren Einsatz das Gewicht von Bauteilen in manchen Fällen um bis zu 50% reduziert werden und somit der ökologische Fußabdruck der Luftfahrtindustrie erheblich reduziert werden. Darüber hinaus haben Bauteile aus Faserverbundwerkstoffen bei korrekter Verarbeitung eine höhere Schlagfestigkeit und Schadenstoleranz als andere gängige verwendete Materialien sowie bessere Korrosionseigenschaften. [3]

Um mit diesem wachsenden Trend Schritt halten zu können, bedarf es einer zunehmenden Digitalisierung und Automatisierung bei der Produktion von Faserverbundbauteilen.

Die Industrie 4.0 und das Internet der Dinge (IoT, engl. Internet of Things) eröffnen neue Möglichkeiten in der Faserverbundverarbeitung, die diese Herausforderungen adressieren. Die Innovationen in dieser Branche führen zu einem Prozessumdenken und die Herstellung von Bauteilen aus Faserverbundwerkstoffen steht einem großen Wandel bevor. Neue Technologien wie der Digitale Zwilling müssen effizient in den Prozess integriert werden, um diesen Wandel bewältigen zu können [4].

Für die Fertigung von Faserverbundbauteilen gibt es verschiedenste Verfahren. Dabei reicht das Spektrum vom manuellen Ablegen der Verbundwerkstoffe bis hin zum maschinengestützten und automatisierten Ablegen der vorimprägnierten Fasern (Prepregs).

In den Anfängen der Produktion von Bauteilen aus Verbundwerkstoffen war der Fertigungsprozess mit einem sehr hohen manuellen Aufwand verbunden, bspw. durch das händische Ablegen der Lagen und deren Zuschnitt. Die manuelle Faserablage ist dabei nicht nur zeitaufwändig, sondern birgt auch Fehlerpotenziale manueller Arbeit, wie mangelnde Präzision und Reproduzierbarkeit. Auch heutzutage finden sich noch immer manuelle Tätigkeiten in der Produktion von Bauteilen aus Faserverbundwerkstoffen. Mit der steigenden Nachfrage wird die Automatisierung des Prozesses zunehmend in den Vordergrund gerückt, um den Prozess produktiver zu gestalten.

Automatisierte Faserablageverfahren bieten aufgrund ihrer Reproduzierbarkeit, Präzision und Schnelligkeit große Vorteile verglichen mit Handlaminierverfahren. Besonders die Möglichkeit Fasern exakt in Belastungsrichtung zu platzieren, steigert das Leichtbaupotential der Bauteile. Die Prozesskette für die Fertigung lastpfadgerecht ausgelegter Bauteile ist bis dato nicht durchgängig, umständlich und bedarf zum Teil manueller Eingriffe. Die einzelnen Prozessschritte sind meist Insellösungen und haben keine konsistenten Schnittstellen zu den vorangehenden oder nachfolgenden Teilschritten [5].

Zu den häufigsten automatisierten Ablageverfahren zählen das Filament-Wickelverfahren (FW, engl. Filament Winding), das automatisierte Tapelegen (ATL, engl. Automated Tape Laying) sowie das Automated Fiber Placement (AFP).

Das FW ist ein Verfahren, bei dem Endlosfasern um einen rotierenden oder feststehenden Kern gewickelt werden. Die Fasern werden unter Spannung auf der Form abgelegt. Durch die Rotation und gleichzeitige lineare Bewegung der Fasern können Schichten mit einer bestimmten Orientierung abgelegt werden. So können je nach Relation zwischen den Bewegungen der Achsen Lagen unterschiedlicher Orientierung abgelegt werden. Mit diesem Verfahren lassen sich hohle, rotationssymmetrische Bauteile mit einem Durchmesser von ca. 25 mm bis 6 m herstellen. Ablageraten von bis zu 45 kg/h können erreicht werden [6], [7]. Somit wird dieses Verfahren häufig zur Herstellung von Rohren oder Tanks verwendet. Das FW beschränkt sich also auf eine geringe Anzahl spezifischer Geometrien und ist so wenig flexibel im Hinblick auf die Bauteilgeometrie [8].

Beim ATL werden breite unidirektionale Tapes aus Faserverbundwerkstoff auf eine Bauteilform abgelegt und mit Hilfe einer Kompressionsrolle auf die Form gepresst. Die Tapes haben meist eine Breite vom 3 bis hin zu 24 Zoll [9]. Der Ablegekopf positioniert das Material entsprechend der NC-Programmierung und schneidet das Tape in einer definierten Position und einem definierten Winkel ab, so dass die gewünschte Geometrie erreicht wird. Dieses Verfahren wird häufig für größere Bauteile mit geringer Krümmung, wie Flügelschalen, eingesetzt. Aufgrund der Breite der Tapes kann mit diesem Verfahren eine hohe Depositionsrate erreicht werden. ATL ist vor allem für zweidimensionale, flächige Bauteile geeignet. Bei stärker gekrümmten Oberflächen kommt es aufgrund der Breite des Tapes vermehrt zu Fehlern wie Faltenbildung. Zu den Vorteilen dieses Verfahrens gehören eine hohe Depositionsgeschwindigkeit, die Möglichkeit, große Bauteile herzustellen, und eine einfache Offline-Maschinenprogrammierung durch relativ einfache fertigbare Geometrien. Nachteilig sind die hohen Investitionskosten für die häufig großen Anlagen, die begrenzte geometrische Komplexität und der höhere Materialabfall im Vergleich zum AFP. [10]

Beim AFP handelt es sich um eine Kombination aus FW und ATL [8]. Bei diesem Verfahren werden bis zu 32 einzelne Tows – zusammengefasst als Tape – auf eine Form aufgebracht. Hierbei lässt sich die Anzahl der abgelegten Tows variabel einstellen. Ähnlich wie beim ATL werden die Tapes durch eine Rolleneinheit auf die Oberfläche gepresst. Durch die schmaleren Tapes können komplexere Geometrien im Vergleich zum ATL abgelegt werden, da diese weniger zu Faltenbildung neigen. Mit diesem Verfahren werden typischerweise 1/8- bis 1-Zoll breite Tapes abgelegt. AFP-Systeme können sowohl mit Roboterarmen als auch mit Portalsystemen realisiert werden. Durch den Einsatz von Robotern kann die Komplexität der Bauteile aufgrund der Freiheitsgerade eines Roboterarms weiter erhöht werden. Verglichen mit dem Einsatz von 5-Achs-Portalsystemen ist dieser kostengünstiger zu realisieren. Mit dem AFP sind generell kleinere, aber dafür komplexere Bauteile im Vergleich zum ATL fertigbar. Mit dem AFP lassen sich durch die schmaleren Tapes sowie kleineren Anlagen geringere Depositionsraten realisieren. In ABBILDUNG 1 ist die Ablage von Fasertape mittels AFP-Verfahren schematisch dargestellt. [11]

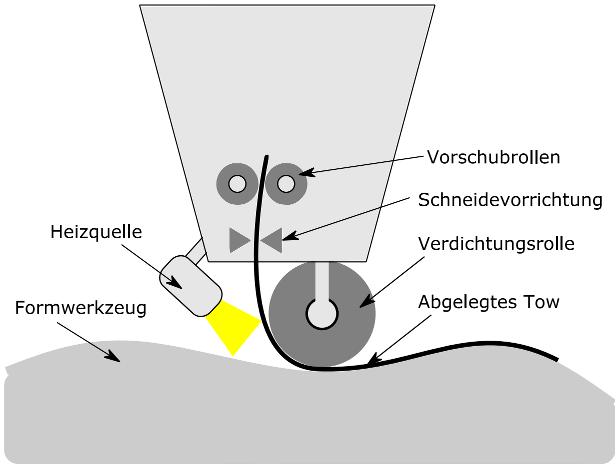


ABBILDUNG 1: SCHEMATISCHE DARSTELLUNG DER DEPOSITION EINES FASERTAPES AUF EINE FORM MITTELS AFP-VERFAHREN

II. USE CASE / PROBLEMSTELLUING

Im Rahmen des Projekts LaiLa [12] in Zusammenarbeit mit der CTC GmbH soll der AFP-Prozess weiterentwickelt und digitalisiert werden. Ziel ist es, eine integrierte Prozesskette zu schaffen, so dass ein einheitlicher Informations- und Datenfluss zwischen den einzelnen Prozessschritten ohne Informationsverluste gewährleistet werden kann. Dabei soll der manuelle Aufwand im Prozess reduziert werden, um mögliche Fehler aufgrund nicht vorhandener Schnittstellen zu minimieren und das Bauteil optimal an die äußeren Belastungen anzupassen.

ABBILDUNG 2 veranschaulicht beispielhaft einen CAD/CAM-gestützten AFP-Prozess. Zwar ist dieser bereits zu Teilen durch Software automatisiert, zeigt aber in der Durchgängigkeit des Informationsflusses Unstetigkeiten auf. Proprietäre Software unterstützt die einzelnen Prozessschritte. Durch diese Insellösungen kommt es zu einem Verlust an Informationen und einem Prozess, der hinsichtlich Effizienz nicht vollständig ausgeschöpft ist.

Im Folgenden wird eine in der Industrie weit verbreitete Prozesskette beschrieben, um die Lücke für die Weiterentwicklung des Prozesses näher darzustellen.

Nachdem ein Bauteil in einem CAD-Programm konstruiert wurde, wird in der Regel eine Finite-Elemente-Analyse (FEA) durchgeführt. Auf Basis dieser FEA wird ein auf den jeweils definierten Lastfall ausgelegter Lagenaufbau mit fester Orientierung der einzelnen Lagen vorgeschlagen. Dieser Vorschlag muss nun manuell auf Plausibilität überprüft und gegebenenfalls angepasst werden. Üblicherweise werden hierbei Orientierungen der Lagen von 0°, 90° und ±45° gewählt. Durch diese Vereinfachung lässt sich der Lagenaufbau leichter und schneller realisieren. Da die vorgeschlagene Faserausrichtungen aus der FEA von diesen einheitlichen Lagenorientierungen abweichen können, wird an dieser Stelle eine Vereinfachung getroffen. Durch die Abweichung von optimaler Faserlage und eigentlichem geplanten Lagenaufbau muss mehr Material als nötig

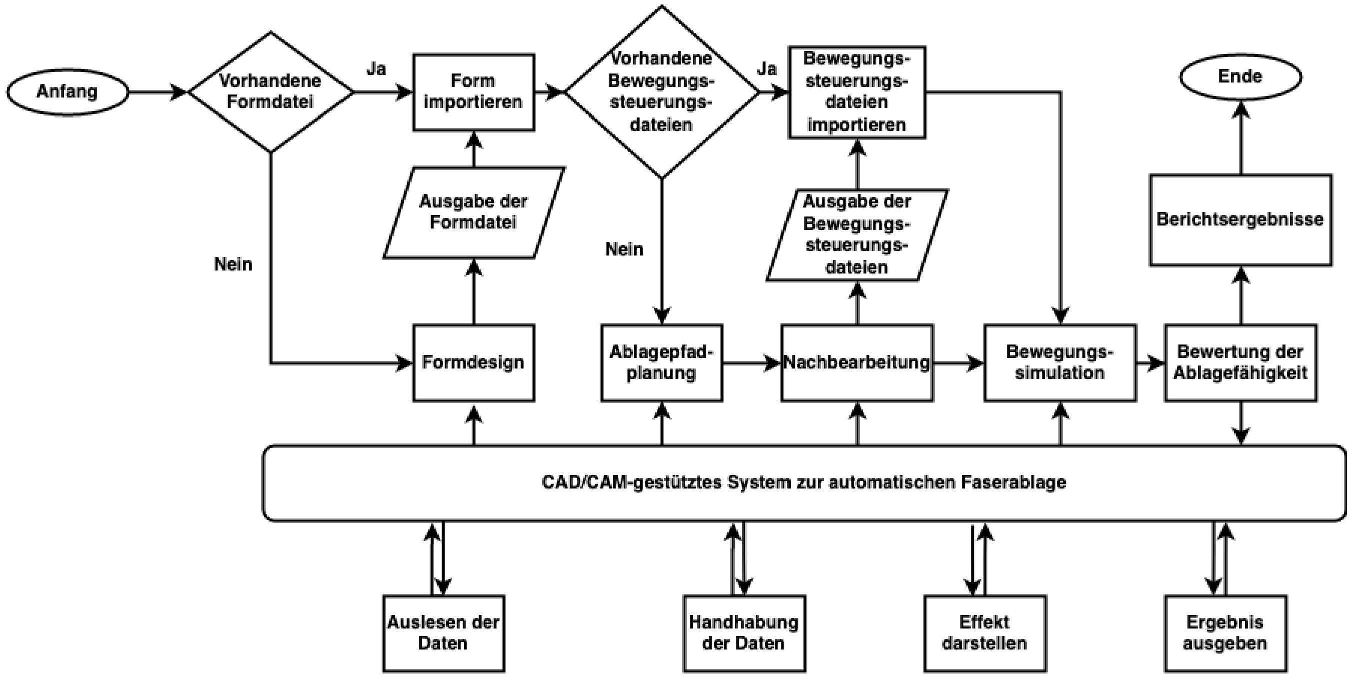


ABBILDUNG 2: BEISPIELHAFTER CAD/CAM-GESTÜTZTER AFP-PROZESS NACH [8]

verwendet werden. Dies sorgt wiederum für einen Anstieg des Gewichts.

Nachdem der Lagenaufbau definiert wurde, gilt es diesen in fertigbare Pfade zu überführen. Daher wird ein weiterer Kompromiss zwischen der optimalen Faserrichtung in den einzelnen Lagen und der tatsächlichen realisierbaren Ablagerichtung aufgrund fertigungstechnischer Restriktionen, wie minimaler Ablageradius oder Tapebreite, gefunden. Diese Übertragung des FEA-Ergebnisses auf den fertigbaren Pfad ist häufig eine manuelle Aufgabe und muss von Fertigungsingenieuren durchgeführt werden.

Im Anschluss an die Pfadplanung beginnt die Fertigung. Dabei werden die einzelnen Pfade nebeneinander- und die Schichten, wie im vorherigen Schritt geplant, von der AFP-Anlage sukzessiv übereinandergelegt. Beim Aufbringen des Materials können unterschiedlichste Fehler auftreten. Dazu gehören unter anderem Überlappungen und Lücken zwischen den abgelegten Tapes. Diese Fehler führen unter anderem zu partiellen Anhäufungen oder fehlendem Material [8]. Eine ungleichmäßige Lastverteilung ist die Folge. In ABBILDUNG 3 sind diese beiden Fehlerarten Lücke (Gap) und Überlappung (Overlap) beispielhaft abgebildet.

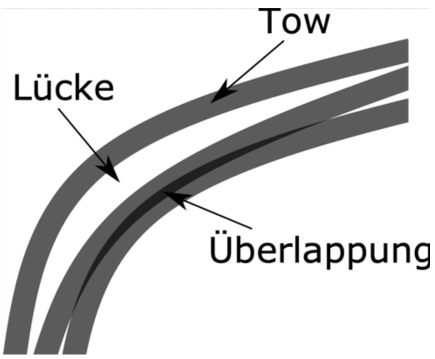


ABBILDUNG 3: SCHEMATISCHE DARSTELLUNGEN AUFTRETENDER FEHLER (LÜCKEN UND ÜBERLAPPUNGEN) IM AFP-PROZESS

Auch die Qualitätssicherung und Fehlererkennung wird oftmals manuell durchgeführt. Eine erheblich längere Produktionszeit sowie erhöhte Ausgaben aufgrund von Personalkosten sind die Folge. Prozessfehler können zu Ausschuss führen und insbesondere bei größeren Bauteilen hohe Kosten verursachen.

Die bisherigen Ansätze der Faserablageverfahren bieten zwar aussichtsvolle Ansätze, bringen jedoch nicht die gewünschte Interoperabilität und Flexibilität mit sich, um den AFP-Prozess zeitig auf die bevorstehenden Herausforderungen vorzubereiten. Methoden und Ansätze aus dem Bereich des FWs und ATLs lassen sich zudem nur begrenzt auf diesen Anwendungsfall übertragen. Vor allem die Einschränkung auf die Fertigung von simpleren Geometrien macht die Übertragbarkeit bestehender Ansätze auf den AFP-Prozess hinfällig. Beim ATL wirken sich kleine Fehler weniger stark auf die Eigenschaften des Bauteils aus, da die Dimensionen des Bauteils die der Fehler häufig um mehrere Potenzen übersteigen. Beim FW lassen sich nur geodätische oder quasi-geodätische Pfade ablegen. Dies schränkt die Freiheit im Design der Bauteile bei der Faserablage erheblich ein [8] und somit wird eine lastpfadgerechte Ablage komplexer Geometrien auf Basis des FEA-Ergebnisses nur begrenzt möglich.

Ein integrierter Prozessablauf über den gesamten Design- und Fertigungszyklus des Bauteils, insbesondere hinsichtlich der Fertigung von Kompositbauteilen mit variabler Steifigkeit, ist derzeit nicht implementiert.

III. BISHERIGE LÖSUNGSANÄTZE

Das Design der Faserpfade hat einen erheblichen Einfluss auf Bauteil- sowie Fertigungseigenschaften wie Qualität, Produktivität, Festigkeit, Gewicht und Herstellungsdauer. Eine durchgängige und integrierte Prozesskette ist daher von großer Bedeutung, um optimierte und reproduzierbare

Kompositbauteile zu fertigen. Einige Softwareentwickler beschäftigen sich seit Jahren mit der Kompatibilität der bestehenden Silolösungen. Wichtig ist, dass Konstruktions- und Fertigungsspezifikationen integriert werden, welche oft im Widerspruch zueinanderstehen.

Coriolis hat auf der JEC 2022 eine Softwarelösung als Integration für *Dassault Systèmes* CATIA und 3DExperience vorgestellt, dass eine einheitliche CAD-CAM-CAE-Umgebung bietet, die Anfang 2023 kommerziell erhältlich sein soll. Hierdurch sollen Besonderheiten des Herstellungsprozesses in der Konstruktionsphase berücksichtigt werden können. Somit würde der Fertigungsingenieur seine fachliche Expertise des Ablegeprozesses nicht, wie aktuell üblich, erst zu einem fortgeschrittenen Stadium des Faser-Pfad-Designs einfließen lassen, sondern von Beginn an im selben System arbeiten. Auch die Problematik der nicht vorhandenen Schnittstellen sowie der Kompatibilität der Datenformate einzelner Softwarelösungen wird durch die Implementierung in einer Softwareumgebung gelöst. [13]

Im Rahmen des Advanced Composites Project (ACP) der National Aeronautics and Space Administration (NASA) wurde ein Software-Tool entwickelt, das ebenfalls die beschriebene Problematik angeht und einen Lösungsansatz für Teile des Problems darstellt. Das Tool Namens Central Optimizer ist ebenfalls in der Lage, Fertigungsdaten in den frühen Phasen des Entwurfsprozesses einzubeziehen.[14], [15]

Die Lösungen ermöglichen allerdings aktuell lediglich klassische Lagenaufbauten, wo jede Schicht homogen mit einer Faserorientierung aufgebaut wird, welche üblicherweise 0°, 90° und $\pm 45°$ beträgt. Die Optimierung und somit die Anpassung an die äußeren Belastungen erfolgen daher durch eine Kombination dieser Schichten. Das Legen von Fasern entlang gekrümmter Pfade für die optimale Ausnutzung der Steifigkeit und Festigkeit ist mit diesen Ansätzen nicht möglich. Die Verwendung von gekrümmten Faserpfaden zur Herstellung von Laminaten mit variabler Steifigkeit wird inzwischen jedoch als vielversprechende Methode angesehen und in vielen wissenschaftlichen Arbeiten untersucht. Einen Überblick über den Stand der Technik im Bereich des fertigungsgerechten Entwurfs für die Herstellung von Bauteilen mit variabler Steifigkeit kann die Veröffentlichung von Lozano et al. verschaffen [16].

IV. Konzept

In dem folgenden Abschnitt wird die Konzeptionierung eines durchgängigen End-to-End-Prozesses am Beispiel des AFP-Verfahrens beschrieben und vorgestellt, wie in Abbildung 4 dargestellt. Ziel des Konzepts ist die Weiterentwicklung eines linearen Ablageprozesses, wie in Abbildung 2 dargestellt, hin zu einem zyklischen integrierten Prozess. Mit Hilfe eines zyklischen Prozesses können Erkenntnisse, die während des Prozessablaufs gewonnen wurden, in der nächsten Anpassung des Bauteils eingebracht und dadurch der Gesamtprozess optimiert werden.

Im Rahmen des Designs wird die Geometrie des Bauteils festgelegt. In diesem Schritt wird das Bauteil entsprechend des Einsatzgebiets und Nutzens konstruiert. Meist wird das Design der Bauteile von CAD-Software unterstützt. Im Rahmen des Designschritts werden noch keine Fertigungsrestriktionen und/oder Materialeigenschaften, die für die spätere Fertigung relevant werden, berücksichtigt. Zwischen dem Design und der Korrektur sollte eine Schnittstelle bestehen, so dass die beschriebene Unkenntnis über Restriktionen im nächsten Designschritt mit beachtet werden.

Das fertig ausgelegte Bauteil wird im Anschluss an den Prozessschritt Berechnung übertragen. In diesem Schritt kommt eine FEM-Software zum Einsatz. Diese nimmt die Geometrie aus der CAD-Software und erstellt ein FEM-

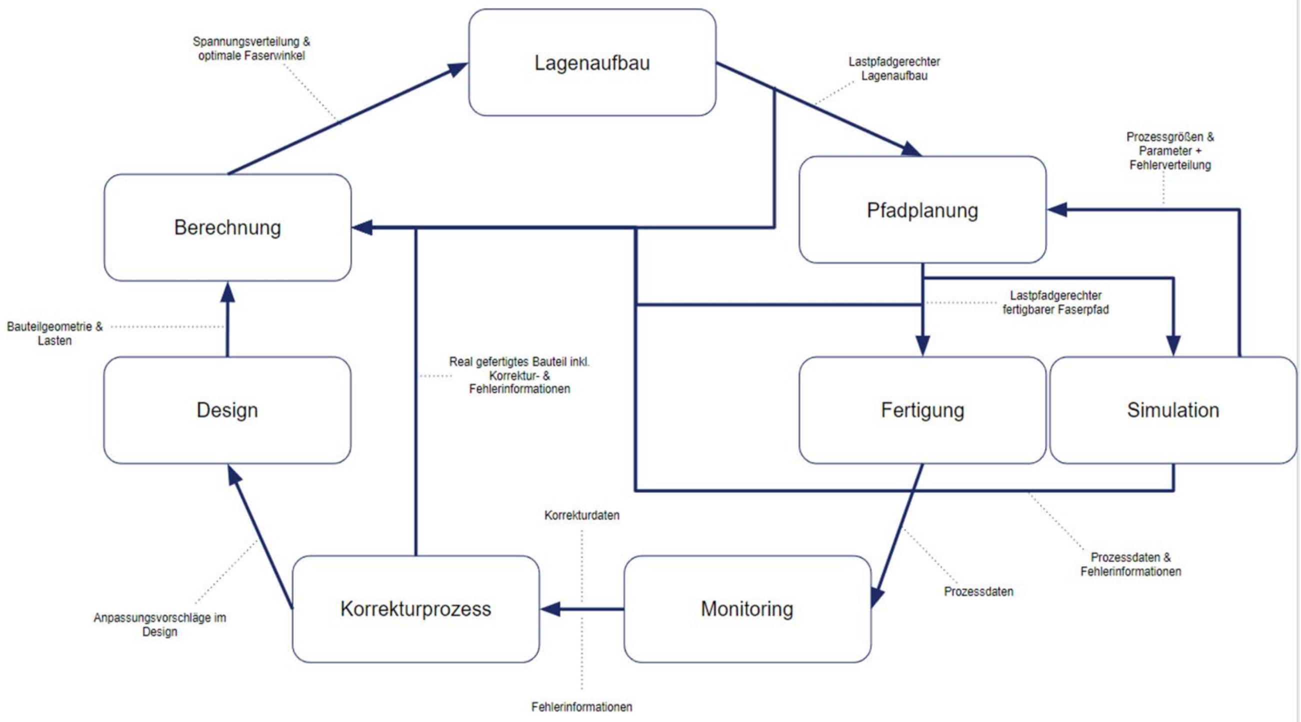


Abbildung 4: Darstellung des vorgestellten Konzepts zum durchgängigen End-to-End-Prozess des APF-Verfahrens

Modell des Bauteils. Durch die Annahme der auf das Bauteil wirkenden Lasten kann der Spannungszustand des Bauteils durch die Software berechnet werden. Die Schnittstelle zwischen Design und Berechnung erfüllt die Anforderungen an eine durchgängige Schnittstelle bereits ausreichend. Häufig werden CAD- und FEM-Software von denselben Herstellern angeboten. Das standardisierte STEP-Datenformat, durch das Produktmodelldaten ausgetauscht werden, können die FEM-Programme verarbeiten und die Berechnung auf Basis der Lasten durchführen. Es wird eine optimale Faserrichtung pro Element des Modells als Ergebnis ausgegeben. Wie im vorherigen Abschnitt bereits beschrieben, sind diese optimalen Faserrichtungen in den seltensten Fällen auch so ablegbar.

Auf Basis der optimalen Faserrichtungen kann ein optimaler Lagenaufbau erzeugt werden. Das Konzept sieht vor, dass in dem Schritt des Lagenaufbaus bereits Prozesswissen einfließt. Somit kann ein Lagenaufbau generiert werden, der auch von dem System abgelegt werden kann. Der fertige Lagenaufbau sollte wieder einer FEA unterzogen werden, um sicherzustellen, dass der neue fertigbare Lagenaufbau den Belastungen standhält oder möglicherweise Material an kritischen Stellen hinzugefügt werden sollte.

In der Pfadplanung werden die einzelnen abzufahrenden Pfade für die Fertigung erzeugt. Mit Hilfe einer Prozesssimulation kann bereits vorab sichergestellt werden, ob der generierte Pfad ablegbar ist. Werden hier bereits Fehler erkannt, werden diese Informationen an die Pfadplanung übermittelt und neue Pfade generiert. Die neuen Pfade stehen in einer Schleife mit der Berechnung. Hierbei wird erneut überprüft, ob die generierten Pfade den gewählten Belastungen standhalten. Spätestens in der Pfadplanung sind die Material- und Fertigungsrestriktionen berücksichtigt. Je eher diese jedoch in den Prozess eingebracht werden, desto eher können später auftretende Fehler vermieden werden. Ferner können durch die Simulation Fehler – vorwiegend Lücken und Überlappungen - simuliert werden. Auch die Simulationsergebnisse der Fehler werden zurück an die Berechnung kommuniziert, um erneut feststellen zu können, ob das Bauteil mit den Fehlern den Belastungen standhält.

Wurde der Lagenaufbau und die Pfadplanung durch die Simulation und erneute FEA validiert, kann das Bauteil gefertigt werden. Dabei wird simultan zur Fertigung der Produktionsprozess überwacht. Hierbei werden einerseits auf Basis des Prozesses anfallende Informationen, wie die Gelenkstellungen des Roboterarms, verarbeitet als auch auf externe Sensorik zurückgegriffen, um mögliche entstehende Fehler zu identifizieren. Häufig werden Laserprofilsensoren oder thermografische Sensoren verwendet, um die Oberflächenbeschaffenheit des Geleges zu erfassen. Diese Fehlerinformationen dienen der Fehlerkorrektur im laufenden Prozess. Durch die Detektion von Lücken und anschließender Auffüllung mittels einer in die erfasste Lücke hineingedruckte Endlosfaser sollen die Fehler ausgebessert werden. Weitere Fehler, wie Überlappungen oder Verdrehungen der Tapes können hierdurch ebenfalls erfasst werden.

Um den Prozesszyklus zu schließen werden die Korrekturinformationen an den anfangs beschriebenen Designschritt übergeben, um aus diesen neue, verbesserte Designkonzepte automatisiert herzuleiten.

V. Forschungsausrichtung

Nachdem das Konzept des digitalen End-to-End-Prozesses vorgestellt wurde, werden in diesem Abschnitt die Anforderungen an den idealen Prozessablauf sowie der Fokus der Forschung des dem Beitrag zugrunde liegenden Projekts erläutert.

Idealerweise werden die in Abbildung 4 dargestellten Prozessschritte des Konzepts von demselben Tool übernommen. Derzeit sind meist unterschiedliche Softwareprogramme an dem Prozess beteiligt. Durch eine vollständige Integration aller Aufgaben in einem Programm sind viele Hürden und Schwierigkeiten, entstehend durch proprietäre Datenformate und Schnittstellen, beseitigt. Alle Prozesse liefen in derselben Umgebung ab und die Informationsübertragung zwischen Prozessschritten würde sich simpel gestalten. Im idealen Prozess ist die manuelle Arbeit minimiert. Fehler aufgrund von menschlicher Arbeit werden reduziert und es kommt zu keiner Verlängerung der Prozesszeit. Sollten Fehler entstehen, werden diese sicher erkannt und online im Prozess korrigiert, so dass ein lastpfadgerechtes und fehlerfreies Bauteil mit minimalen Materialeinsatz gefertigt werden kann. Der gesamte Prozess sollte so ausgelegt sein, dass durch jede Iteration eine Verbesserung des Ergebnisses erzielt wird.

Generell zielt der digitale Prozess auf eine Entlastung der Prozessbeteiligten ab. Dabei wird nicht von einer Substitution gesprochen. Vielmehr soll das Prozesskonzept unterstützend wirken und im Hinblick auf die Wertschöpfungskette den maximalen Output bei minimalen Ressourceneinsatz erzielen.

Dieses Projekt befasst sich insbesondere mit den Schnittstellen zwischen Berechnung, Lagenaufbau und der Pfadplanung sowie mit der Online-Korrektur des AFP-Prozesses. Nach [8] liegen gerade in diesen Bereichen große Potenziale und Forschungsbedarf. Wie bereits in den vorangegangenen Abschnitten beschrieben, gibt es Möglichkeiten, bei der lastpfadgerechten Ablage der Fasern auf Basis der FEM-Berechnung, Material und Gewicht zu sparen. Auch durch die Korrektur der Fehler lassen sich frühzeitig kostenintensive Nachbesserungen oder Neufertigungen vermeiden.

Im Rahmen der lastpfadorientieren Pfadplanung werden unterschiedliche Ansätze entwickelt und auf ihre Anwendbarkeit in der Praxis hin überprüft. Es werden einerseits Methoden erprobt, die als Basis die Ergebnisse der Berechnung nehmen und diese in ablegbare Pfade überführen. Andererseits wird auch erforscht, wie sich die Herangehensweise aus fertigungstechnischer Sicht verhält. Hierbei bilden die Restriktionen des Prozesses die Grundlage. Anders als in dem ersten Ansatz werden nun fertigbare Pfade an die optimalen Faserwinkel angenähert.

Entstehende Fehler sollen durch ein Online-Monitoringsystem erfasst werden. Mit Hilfe der Prozessinformationen kann das real abgelegte Bauteil digital rekonstruiert und dieses wieder mittels einer FEA analysiert werden. Zudem können einige durch den Monitoringprozess erkannte Defekte während des laufenden Prozesses behoben werden. Ein Ziel hierbei ist die Detektion von auftretenden Lücken – durch Verrutschen der Tapes oder Ungenauigkeiten des Ablegesystems – und anschließender Auffüllung der Lücken durch die Deposition einer Endlosfaser unter Verwendung des Fused Filament Fabrication, eines der am weitesten verbreiteten 3D-Druck-Verfahren.

VI. ZUSAMMENFASSUNG

Mit einer weiterführenden Digitalisierung und Automatisierung der Faserablageprozesse wird einerseits die Reproduzierbarkeit erhöht und andererseits die Fehlerhäufigkeit minimiert. Der Fokus dieser Arbeit lag auf dem AFP-Prozess, da der Prozess die Fertigung komplexerer Bauteile ermöglicht. Bestehende Ansätze aus ähnlichen Faserablageverfahren können prozessbedingt nicht auf diesen Prozess übertragen werden. Aktuelle Lösungsansätze für den AFP-Prozess sind unvollständig und noch in der Entwicklung. Besonders die Entwicklung von Ansätzen, die nicht den traditionellen manuellen Aufbau automatisieren, sondern das Potential des Prozesses, beispielsweise durch das Ablegen lastpfadgerechter gekrümmter Fasern, weiter ausschöpfen, sind von großer Bedeutung. Die weitere Forschung in diesen Bereichen würde zu einem besseren Prozessverständnis führen und es ermöglichen einen umfangreichen Digitalen Zwilling zu erstellen. In dem vorliegenden Beitrag wurde ein umfassendes Konzept für einen integrierten und durchgängigen End-to-End-Prozess für das AFP-Verfahren vorgestellt. Eine Umsetzung dieses Konzepts ist im Rahmen des Projekts LaiLa mit Fokus auf der lastpfadgerechten Pfadplanung und der Online-Korrektur des Prozesses weiter vorgesehen. Ergebnisse und Verwendbarkeit der weiteren Forschung werden in zukünftigen Veröffentlichungen gezeigt. Das vorgestellte Konzept wird anhand eines AFP-Systems im Weiteren weiterentwickelt und ergänzt. Das Konzept wird als Teil der Laila-Modelfabrik, welche eine physische Versuchsumgebung darstellt, umgesetzt und validiert. Die Modelfabrik dient als zentrales Element von LaiLa zur Erforschung und Validierung von innovativen CFK-Fertigungsprozessen.

DANKSAGUNG

Die Autoren des Projekts LaiLa bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr.

LITERATUR

[1] W. Seneviratine, "The aerospace market - state of the industry report 2020," American Composite Manufacturing Association, 2020.

[2] S. Shparberg and B. Lange, "Airbus Global Market Forecast 2022," Toulouse, Jul. 2022.

[3] M. Maria, "Advanced composite materials of the future in aerospace industry," *INCAS BULLETIN*, vol. 5, no. 3, pp. 139–150, Sep. 2013, doi: 10.13111/2066-8201.2013.5.3.14.

[4] R. Harik, "neXt automated fiber placement: advancing composites manufacturing towards a new paradigm," *SAMPE Journal*, vol. November/December, no. 2020, pp. 6–14, 2020, [Online]. Available: www.sampe.org

[5] A. Brasington, C. Sacco, J. Halbritter, R. Wehbe, and R. Harik, "Automated fiber placement: A review of history, current technologies, and future paths forward," *Composites Part C: Open Access*, vol. 6, p. 100182, Oct. 2021, doi: 10.1016/J.JCOMC.2021.100182.

[6] D. Jayasekara, N. Y. G. Lai, K. H. Wong, K. Pawar, and Y. Zhu, "Level of automation (LOA) in aerospace composite manufacturing: Present status and future directions towards industry 4.0," *J Manuf Syst*, vol. 62, pp. 44–61, 2022, doi: 10.1016/j.jmsy.2021.10.015.

[7] A. McIlhagger, E. Archer, and R. McIlhagger, "Manufacturing processes for composite materials and components for aerospace applications," in *Polymer Composites in the Aerospace Industry*, Elsevier, 2015, pp. 53–75. doi: 10.1016/B978-0-85709-523-7.00003-7.

[8] L. Zhang, X. Wang, J. Pei, and Y. Zhou, "Review of automated fibre placement and its prospects for advanced composites," *J Mater Sci*, vol. 55, no. 17, pp. 7121–7155, Jun. 2020, doi: 10.1007/s10853-019-04090-7.

[9] P. Boisse, *Advances in Composites Manufacturing and Process Design*. Elsevier, 2015. doi: 10.1016/C2014-0-02644-5.

[10] D. H.-J. A. Lukaszewicz, C. Ward, and K. D. Potter, "The engineering aspects of automated prepreg layup: History, present and future," *Compos B Eng*, vol. 43, no. 3, pp. 997–1009, Apr. 2012, doi: 10.1016/j.compositesb.2011.12.003.

[11] K. Yassin and M. Hojjati, "Processing of thermoplastic matrix composites through automated fiber placement and tape laying methods: A review," *Journal of Thermoplastic Composite Materials*, vol. 31, no. 12, pp. 1676–1725, 2018, doi: 10.1177/0892705717738305.

[12] "Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr, LaiLa – ein Labor für die intelligente Leichtbauproduktion." https://dtecbw.de/home/forschung/hsu/projekt-laila/laila (accessed Aug. 28, 2022).

[13] Francois Melocco, "Future Composites: Combining Accessible Design, Scalable Simulation & Reliable Manufacture , JEC World 2022 DAY 2."

[14] C. Craig and N. August, "Verification and Validation of Integrated Design and Manufacturing Analysis Tool for AFP Structures," in *SAMPE neXus 2021*, 2021, vol. 2021-June, pp. 1100–1121. doi: 10.33599/nasampe/s.21.0578.

[15] A. T. Noevere and C. Collier, "Design for Manufacturing Tool for Automated Fiber Placement Structures – Verification and Validation," in *AIAA Scitech 2020 Forum*, Jan. 2020, vol. 1 PartF, pp. 1–20. doi: 10.2514/6.2020-1477.

[16] G. G. Lozano, A. Tiwari, C. Turner, and S. Astwood, "A review on design for manufacture of variable stiffness composite laminates," *Proc Inst Mech Eng B J Eng Manuf*, vol. 230, no. 6, pp. 981–992, 2016, doi: 10.1177/0954405415600012.

LaiLa Modellfabrik - Eine Validierungsplattform für Künstliche Intelligenz im Bereich Cyber-Physischer Produktionssysteme im Leichtbau

Anna Nordhausen*, Jonas Ehrhardt,
Nantwin Möller
Institute of Automation
Helmut Schmidt University
Hamburg, Germany
*anna.nordhausen@hsu-hh.de

***Kurzfassung* – Neue Methoden aus den Bereichen Künstliche Intelligenz (KI) und Maschinelles Lernen (ML) sind häufig datengetrieben. Um eine erfolgreiche Anwendung in KI oder ML zu garantieren, müssen Datensätze breite Fehlerverteilungen sowie hohe Varianzen in der Fertigungssystemkomplexität und dem Einsatz verschiedener Fertigungsverfahren besitzen. Existierende Datensatze spiegeln dies zumeist nicht wider. Aus diesem Grund wird im Forschungsprojekt "LAboratorium für Intelligente LeichtbAuproduktion" (LaiLa) eine Modellfabrik für mehrstufige Produktions- und Fertigungsprozesse im seriellen Leichtbau geschaffen. Mithilfe der Modellfabrik sollen unter anderem realistische Datensätze aufgezeichnet werden, welche von verschiedenen Verfahren aus KI und ML sowie variierenden Zielstellungen verwendet werden können. Im Folgenden werden drei Zielstellungen, welche mit drei verschiedenen ML Verfahren im Rahmen des Forschungsprojekts LaiLa adressiert werden, vorgestellt: Roboterpfadregelung beim Ultraschallschweißen von Thermoplasten mit Reinforcement Learning, Generative Modelle zur Erstellung von Trainingsdatensätzen bei der Fehlerklassifikation von additiv gedruckten Bauteilen und das Lernen von Repräsentationen von Produktionsprozessen bei der Planung neuer oder veränderter Prozesse. Mithilfe des Modellfabrikkonzepts können diese Verfahren, neben existierenden artifiziellen Benchmarks, validiert werden.**

Stichworte - Künstliche Intelligenz, Maschinelles Lernen, Reinforcement Learning, Generative Modelle, Repräsentationslernen

I. Einleitung

Digitalisierungs- und Automatisierungsthemen halten in der Industrie weiterhin Einzug. Je mehr Prozesse automatisiert und digitalisiert werden, desto mehr Prozessdaten können hierzu aufgenommen und mithilfe neuer Verfahren analysiert werden. In vielen Fällen haben sich Automatisierungslösungen bereits in Unternehmen etabliert, jedoch bleiben die Erkenntnisse häufig ungenutzt oder es findet nur eine teilweise Nutzung statt.

Es kommt hinzu, dass es nur sehr wenige reale Datensätze gibt, die der Forschung zur Verfügung gestellt werden. Dies liegt daran, dass Unternehmen oftmals befürchten, zusammen mit den Daten auch Unternehmensgeheimnisse preiszugeben. Ebenso umfassen reale Datensätze häufig nur geringe Varianzen und Variabilitäten. Fehler finden in realen Szenarien nur selten statt, sodass diese oft nicht in den Datensätzen enthalten sind. [1]

Des Weiteren ist die Auslastung von Realsystemen in Industrieunternehmen häufig so hoch, dass eine Nutzung für Forschungszwecke oft nicht möglich ist. Die Folge ist, dass nur wenige ausreichende Tests durchgeführt werden können und die Datenquantität, wie auch -qualität nicht ausreichend sind.

Im Rahmen des Forschungsprojekts "LAboratorium für Intelligente LeichtbAuproduktion"(LaiLa) wird aktuell eine Modellfabrik geschaffen, welche unter anderem die Möglichkeit bietet, in einem industriellen Umfeld unter Realbedingungen, Datensätze verschiedenster Art, insbesondere für Methoden der Künstlichen Intelligenz (KI) und des Maschinellen Lernens (ML), aufzunehmen. Ebenso können eine Vielzahl von Forschungsansätzen in den Bereichen Digitalisierung und Automatisierung vorangetrieben werden, um neue Sprunginnovationen zu erreichen. Kern des Laboratoriums ist eine intelligente Modellfabrik, welche als Demonstrations-, Schulungs- und Validierungsplattform für neue Ideen, Konzepte und Verfahren in der Domäne Leichtbau dienen soll. Sie besteht aus modernen Cyber-Physischen Produktionssystemen. [2]

Dieser Beitrag befasst sich mit verschiedenen Möglichkeiten des Einsatzes von Methoden der KI, die sich aus der Nutzung der Modellfabrik in LaiLa ergeben. Der Beitrag ist wie folgt aufgeteilt. Kapitel II befasst sich mit der Modellfabrik im Allgemeinen. In Kapitel III wird ein Konzept zur Nutzung von Bestärkendem Lernen im Kontext von LaiLa vorgestellt. Anschließend werden im Abschnitt IV Generative Modelle im industriellen Kontext erklärt, woran Abschnitt V über das Repräsentationslernen anschließt. Der Beitrag schließt mit einer Zusammenfassung und einem Ausblick ab.

II. Modellfabrik

Im folgenden Absatz wird das Konzept der Modellfabrik erläutert. Der Aufbau wurde basierend auf einem Demonstratorprodukt (s. Abb. 2), in annähernd an dessen Fertigungsprozess, konzeptioniert. Ein übergeordnetes Datensammelkonzept ermöglicht die Aufzeichnung hochqualitativer Datensätze für KI und ML Anwendungen in verschiedenen Domänen.

https://doi.org/10.24405/14556

Da es sich beim Forschungsprojekt LaiLa um ein Laboratorium für Leichtbautechnik handelt, wurden die damit einhergehenden Produktionstechniken bei der Herstellung des Demonstratorprodukts berücksichtigt (s. ABBILDUNG 1). Das Demonstratorprodukt besteht aus einer konvexen, gepressten Thermoplastschale, auf der, wie im Flugzeugbau üblich, Versteifungsstreben befestigt sind. Um das gängige, jedoch aufwendige, Verfahren des Vernietens der Einzelteile abzulösen sind die Versteifungsstreben des Demonstratorprodukts mithilfe des Ultraschallschweißverfahrens gefügt. Es werden zwei unterschiedliche Versteifungsstrebenprofile verwendet, um eine umfangreiche Evaluierung der alternativen Fügemethode zu ermöglichen. Des Weiteren sind auf der Schale Halteschellen aufgebracht, welche additiv gefertigt wurden. Diese sind durch Klebeverbindungen gefügt und dienen als Aufnahme eines, mit vorimprägnierten Kohlefasern gewickelten, Wasserstofftanks. Die Herausforderung bei dieser Anordnung besteht in der Genauigkeit und Qualität, da die Aufnahme des Tanks durch Steckachsen erfolgen soll. Die Aufnahmetechnik durch Stäbe soll das Fügen von Aufhängungsstrukturen in Seitenleitwerken von Flugzeugen wiederspiegeln und die Validierungsplattform für einen automatisierten Klebeprozess darstellen.

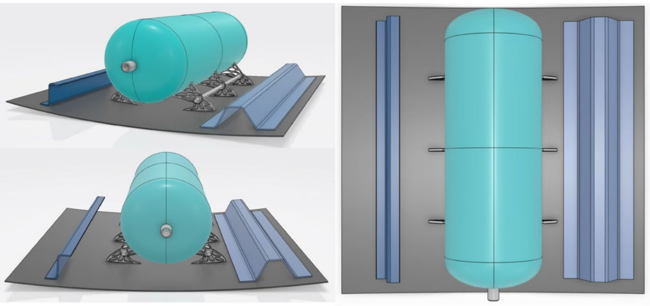


ABBILDUNG 1: DEMONSTRATORPRODUKT DER LAILA MODELLFABRIK. AUF EINER KONVEXEN THERMOPLASTSCHALE SIND VERSTEIFUNGS-STREBEN AUFGESCHWEIßT. GEKLEBTE HALTESCHELLEN NEHMEN EINEN, MIT KOHLEFASERN GEWICKELTEN, WASSERSTOFFTANK ÜBER EINE STECKACHSENVERBINDUNG AUF. [2]

Die einzelnen Fertigungstationen des Herstellungsprozesses wurden so gewählt, dass einzelne, zu erprobende Verfahren, auch losgelöst von einem seriellen Fertigungsfluss getestet und evaluiert werden können. Alle Fertigungstationen können mit einem Automated Guided Vehicle (AGV) entweder aus dem Materialeingang oder dem Lager beliefert werden. Im Materialeingang befindet sich neben einer Eingangsprüfstation eine NC-Schneidemaschine, die für den Zuschnitt von Kohlefasertextilen und anderen Halbzeugen verwendet werden kann. Halbzeuge können von dort entweder direkt an Fertigungsstationen geliefert oder in einem Lager zwischengelagert werden. Die erste Fertigungsstation befasst sich mit der automatischen Faserablage zur Herstellung von gewickelten Wasserstofftanks aus vorimprägnierten Kohlefasern mittels eines Roboters. In einer Laborpresse können die Thermoplastschalen, welche als Grundplatte des Demonstratorprodukts dienen, mit regulierbaren Temperaturen und Drücken umgeformt werden. Die Laborpresse ermöglicht weiterhin die Fertigung von Bauteilen im Resin Transfer Molding Verfahren, welches für zukünftige Produkte und Versuchsaufbauten weitere Verwendung findet. In einer Oberflächenbearbeitungsstation können Grate oder Unebenheiten entfernt, sowie Oberflächen für die Folgeverfahren vorbereitet werden. Eine Ultraschallschweiß- und Klebezelle ermöglicht das automatisierte Auftragen von Fügungspasten mit Robotern. Des Weiteren ist die Zelle mit einer Sonotrode zum robotergestützten Ultraschallschweißen ausgestattet. Eine optische Vermessungsstation ermöglicht eine quantitative Evaluation der eingesetzten Fertigungsverfahren.

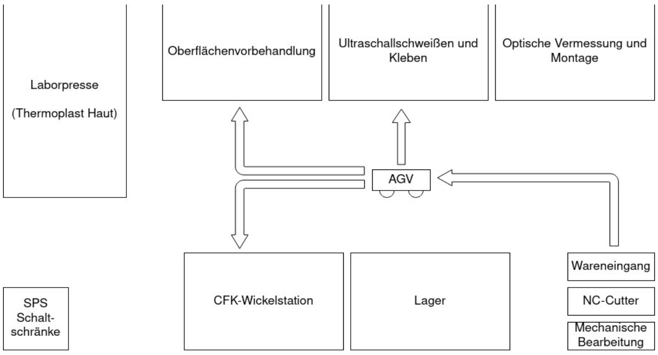


ABBILDUNG 2: KONZEPTIONELLE AUFTEILUNG DER LAILA MODELLFABRIK. DIE FERTIUNGSSCHRITTE SIND SEQUENTIELL IN EINER RINGFORM ANGEORDNET. ALLE STATIONEN LASSEN SICH MIT EINEM AUTOMATED GUIDED VEHICLE BELIEFERN. IN ANLEHNUNG AN [2]

Jede Station der LaiLa Modellfabrik wird mit einem Edge Device ausgestattet, das sowohl kontinuierliche, als auch diskrete Daten aus den vernetzten Anlagen aufzeichnet. Die Daten werden in einheitlichem Format in einem SCADA System abgelegt und für Forschungszwecke sowie intern zugänglich gemacht.

III. BESTÄRKENDES LERNEN

Bestärkendes Lernen oder auch Reinforcement Learning (RL) ist neben Supervised und Unsupervised Learning ein Teilgebiet von ML. Beim RL versucht ein sogenannter Agent durch numerische Belohnungen zu lernen und ein gesamtheitlich betrachtetes Problem zu lösen. Ziel ist es hierbei, die Gesamtheit der Belohnungen zu maximieren. Neben dem lernenden Agenten gehören eine Umgebung (environment), eine Strategie (policy), ein Belohnungssignal (reward) und eine Wertefunktion (value function) bzw. ein Modell der Umgebung [3] zur Idee des RL. Das bedeutet, dass RL Agenten explizite Ziele verfolgen, Aspekte der Umgebung wahrnehmen können und Aktionen wählen, die die Umgebung beeinflussen. Durch die Strategie wird festgelegt, wie sich der Agent zu einem bestimmten Zeitpunkt verhalten soll. Sie stellt somit ein Abbild der wahrgenommenen Zustände der Umgebung auf in diesen Zuständen ausführbare Aktionen dar. Mit dem Belohnungssignal wird das Ziel in einem RL-Problem beschrieben, da dieses langfristig maximiert werden muss. [3]

Im RL wird der sogenannte 'trial-and-error'-Ansatz verfolgt, welcher besagt, dass dem lernenden Agenten im Vorhinein nicht bekannt ist, welche Handlungen bzw. Aktionen zielführend sind. Vielmehr müssen diese durch Ausprobieren herausgefunden werden. Hierbei spielt die Verteilung zwischen Exploration, dem Ausprobieren, und Exploitation, dem Nutzen von Wissen, eine entscheidende Rolle. Der Agent muss, um eine optimale Lösung zu finden, eine Vielzahl von Aktionen ausprobieren, um nach und nach die Aktionen zu wählen, die die höchste Belohnung herbeiführen. Belohnungssignale sind unmittelbar, wohingegen Wertefunktionen langfristig einen Aufschluss darüber geben, welche Aktionen sinnvoll sind. Das

Umgebungsmodell dient dazu, Ruckschlüsse auf das Verhalten der Umgebung zuzulassen. [3]

A. . Use Case Regelung und Anomalieerkennung im Ultraschallschweißen

Das Projekt LaiLa fokussiert sich im Use Case ’Ultrasonic Welding’ auf die Qualitätssicherung durch Digitalisierungsaspekte im automatisierten Ultraschallschweißprozess. Hierfür sollen Sensor- und Schweißdaten genutzt werden, um ein vollumfängliches Konzept zur Qualitätssicherung zu erstellen (s. ABBILDUNG 3). Die Speicherung der aufgenommenen Daten ist daher unumgänglich. Mithilfe eines Reinforcement Learning Ansatzes soll zukünftig der Schweißbahnprozess korrigiert sowie Anomalien erkannt werden. [4]

Derzeit besteht keine Möglichkeit, Prozessparameter während des Schweißprozesses, welcher nur einige Sekunden andauert, zu andern bzw. anzupassen. Aufgrund äußerer und innerer Einflüsse führt dies dazu, dass eine Abweichung der Schweißqualität entlang der Schweißnaht entstehen kann. Ebenso werden die derzeit aufgenommenen Prozessdaten auf einem lokalen Datenträger, mit begrenzter Aufzeichnungsrate, gepeichert und sind nicht global zuganglich. Mithilfe eines RL-Ansatzes soll zukünftig gelernt werden, wie Prozessparameter während des Prozesses geregelt werden können und Anomalien entgegengewirkt werden kann. [4]

Laut aktuellen Forschungsergebnissen, ist heute noch kein generalisierbarer RL-Ansatz für die Anomalieerkennung in Industrieunternehmen vorhanden. Je nach Problemschwerpunkt, werden unterschiedliche Verfahren eingesetzt. [5] Der Ansatz von Pang et al. ist beispielsweise sinnvoll, wenn man einen überwachten Anomalieerkennungsansatz mit wenigen gelabelten Daten trainieren möchte. Dieser stößt jedoch bei zu geringer Dimensionalität der Daten an seine Grenzen. [6] Sollten die Dimensionsräume der Daten zu groß sein, wird es notwendig, diesen auf das Notwendigste zu reduzieren, um entsprechende Merkmale, zur verbesserten Vorhersage, extrahieren zu können. Mit einem so genannten Differenzialgorithmus kann mit hochdimensionalen Merkmalsraumen¨ umgegangen werden und die Robustheit, auch bei nichtlinearen Beziehungen, bleibt bestehen. [7] [8] Weiterhin kann mit dem RL-Ansatz von Jomaa et al. die beste Konfiguration der Hyperparameter eines Prozesses gelernt werden, um eine Anomalieerkennung möglichst wenig einzuschränken. [9]

B. Konzept

RL stellt, aufgrund der Fähigkeit, komplexes Verhalten in hochdimensionalen Daten zu lernen [5], ein interessantes Forschungsfeld dar, wenn die Regelung und Anomalieerkennung komplexer Industrieprozesse untersucht werden soll. Das verfolgte Konzept (s. ABBILDUNG 4) basiert auf zwei Teilbereichen, die aufeinander aufbauen. Zunächst wird mittels der aktuellen Sensordaten sowie Prozessparameter eine Regelung des Ultraschallschweißprozesses angestrebt. Mittels einer Simulation können potenzielle Algorithmen trainiert, validiert und getestet werden. Hierbei wird der Agent bei einem korrekten Regelschritt positiv belohnt. Andernfalls erhalt der Agent eine negative Belohnung. Die Bewertungsfunktion wird auf Grundlage der Toleranzwerte und Restriktionen erstellt. Die Validierung verschiedener RL-Ansätze gibt Aufschluss über die Nutzbarkeit der Algorithmen.

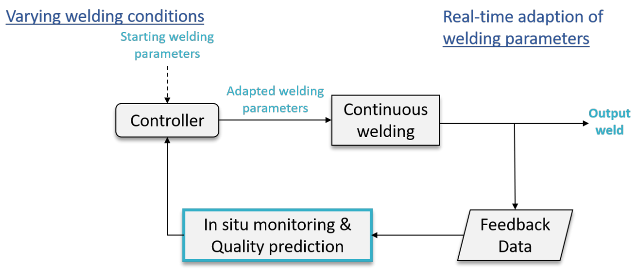


ABBILDUNG 3: SKIZZE DES ZUKÜNFTIGEN CLOSED-LOOP ULTRASCHALLSCHWEIßPROZESSES IN ANLEHNUNG AN [4].

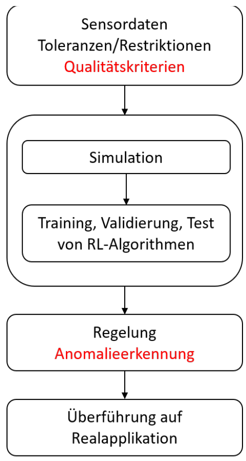


ABBILDUNG 4: KONZEPTSKIZZE DER REGELUNG MIT RL IM ULTRASCHALLSCHWEIßPROZESS UND DIE ERWEITERUNG ZUR ANOMALIEERKENNUNG (ROT.)

Weiterhin wird untersucht, inwiefern sich RL-Algorithmen für eine Anomalierkennung eignen. Neben den Toleranzwerten und Restriktionen, werden zusätzlich Qualitätskriterien für den Ultraschallschweißprozess berücksichtigt. Es muss daher sichergestellt werden, dass während des Prozesses die aufgenommenen Daten zügig verarbeitet und zurückgegeben werden, sodass eine Prozessanpassung erfolgen kann. Dies stellt lediglich eine der Herausforderungen dar. Ziel ist es, ein Assistenzsystem zu erstellen, welches auf Unregelmäßigkeiten reagieren und diesen bereits während des Prozesses entgegenwirken kann.

IV. GENERATIVE MODELLE FUR DIE ADDITIVE¨ FERTIGUNG

Ist ein bestehender Datensatz zu klein bzw. zu homogen, wirkt sich dies negativ auf das Ergebnis des ML aus. In solchen Fällen werden Generative Modelle genutzt, um die Merkmalsverteilung einzelner Klassen in Trainingsdatensätzen zu erlernen. Darauf basierend können anschließend neue, realitatsnahe Daten generiert und somit die Datenbasis, für das Trainieren von künstlichen neuronalen Netzen (KNN), vergrößert werden. Durch die Vergrößerung des Datensatzes können Homogenitäten kompensiert und Overfitting vermieden werden. Synthetische Bilddatenerweiterung wird aber auch verwendet, wenn bereits eine große Datenbasis besteht. In den meisten Fällen wird dadurch das Lernergebnis verbessert [10]. Dabei ist zu beachten, dass reale Daten besser für das Training sind, als Synthetische. Aktuell werden für die Datengeneration vorwiegend Generative Adversarial Network (GAN) und

Variational Autoencoder (VAE) genutzt, wobei laut [11] mit dem GAN qualitativ bessere Ergebnisse erreicht werden.

A. Use Case Fehlererkennung im 3D-Druck

Die Bauteilqualität stellt eine immer wichtigere Anforderung dar. Aufgrund der langen Herstellungszeit, welche mit den komplexen Strukturen des verwendeten Materials sowie des additiven Prozesses zu tun hat, ist das frühzeitige Detektieren und Klassifizieren von Herstellungsfehlern essenziell. Dies ist im Sinne der Kosten- und Ressourceneinsparung sowie der effizienten Nutzung von Maschinen von höchster Relevanz. Aus diesen Gründen wird im Rahmen dieses Use Cases eine Methode zur zuverlässigen, datengestützten Fehlerdetektion entwickelt. Ziel ist es, den Bauprozess visuell zu überwachen und Defekte zu erkennen, zu klassifizieren und Korrelationen mit den Prozessparametern herzustellen.

B. Konzept

Für die Detektion von Fehlern in komplexen Bildern sind neuronale Netze besonders geeignet, da sie Klassifikationsraten von über 95% erreichen. Jedoch werden für das Training dieser Netze umfangreiche Datensätze benötigt. Da ein entsprechender Datensatz für diese Anwendung noch nicht zur Verfügung steht, wird eine Methode erarbeitet, mit der ein solcher generiert werden kann.

Im Fokus steht hier das Generative Adversarial Network (GAN). Dieses Artefakt soll sowohl für den Anwendungsfall, als auch für weitere artverwandte Anwendungsfälle nutzbar sein. Voraussetzung für das Training des GAN ist eine Menge x realer Bilder, die während des Druckprozesses von Bauteilen im Bauraum aufgenommen werden. Dazu wird ein Kamerasystem, ein 3D-Drucker sowie die gerätespezifischen Informationen (z.B. Große des Bauraums, Ausrichtung der Kamera in Relation zum Bauraum) benötigt. Außerdem sollen 3D-Modelle von Druckbauteilen, als weitere Informationsquelle, genutzt werden. Die Deep Convolution-Architektur eignet sich besonders zur Verarbeitung von Bilddaten. Die Conditional-Architektur ist notwendig, um nach abgeschlossenem Training, gezielt Bilder einer bestimmten Klasse zu generieren. Der Multiconditional-Ansatz ist ebenfalls erforderlich, da die Eingabe aus mehreren Komponenten besteht. Mit dem StyleGAN können Teilbereiche des Bildes mit Fehlermerkmalen versehen werden.

Ist das GAN trainiert, kann ein Datensatz erzeugt werden, der abhängig von der Vorgabe neuer 3D-Modelle, entsprechende synthetische aber realistische Bilder dieses Bauteils im Bauraum beinhaltet. Auch soll die Möglichkeit bestehen, den Blickwinkel auf alte bzw. bekannte Bauteile, die Szenerie des genutzten 3D-Druckers sowie das Einbringen von Defekten zu variieren. Mit diesem individualisierten Datensatz kann anschließend ein klassifizierendes neuronales Netz (z.B. ein CNN) trainiert werden, um die im laufenden Druckprozess aufgenommenen Bilder auf Fehler zu inspizieren und eine Klassifikation vorzunehmen.

V. Repräsentationslernen für die Planung von Produktionsprozessen

Repräsentationslernen ist eine Domäne aus dem Bereich ML. Das Repräsentationslernen beschäftigt sich mit dem Erlernen möglichst informationsreicher und eindeutiger Repräsentationen von Daten. [12] Diese ermöglichen eine verbesserte Leistungsfähigkeit von existierenden Algorithmen sowie Netzwerken. Insbesondere zum Transferlernen, also der Fähigkeit eines Lernalgorithmus Ähnlichkeiten zwischen verschiedenen Lernaufgaben auszunutzen, um seine statistische Aussagekraft zu starken, sind informationsreiche Datenrepräsentationen hilfreich. So kann der Raum ähnlicher Features aufgeweitet werden. [12].

Neben dem klassischen Repräsentationslernen, also dem Lernen von Datenrepräsentationen, lassen sich auch Repräsentationen mathematischer Zusammenhänge aus Daten erlernen und in neuronalen Netzen encodieren. Hierbei werden, durch sich wiederholendes Training, komplexe Gleichungssysteme vom latenten Raum neuronaler Netze nachgebildet. Durch das Lernen aus Beobachtungen und Messungen, ermöglicht sich so beispielsweise das Nachbilden physikalischer Materialmodelle, welche als Eingabe des neuronalen Netzes dienen.

A. Use Case Planung in der Modellfabrik und im Ultraschallschweißen

Die Planung von Produktionsprozessen stellt eine Kernkompetenz für produzierende Unternehmen dar [13]. Während symbolische Planungsverfahren, wie auf semantischen Beschreibungen basierende Suchverfahren, logische Agenten oder Grammatiken schon einen Korpus an Literatur aufweisen können, sind subsymbolische Planungsverfahren noch wenig erforscht. [14], [15] Subsymbolische Planungsverfahren stutzen sich insbesondere auf numerische Daten, die keine Semantik oder Symbolik enthalten.

Im Projekt LaiLa werden in zwei Use Cases subsymbolische Planungsverfahren erforscht. Der Use Case Ultraschallschweißen beschäftigt sich mit dem automatisierten Ultraschallschweißen von Thermoplasten. Die Schweißdaten des Ultraschallprozesses können dazu verwendet werden, eine Repräsentation der physikalischen Prozesse im Material während des Schweißprozesses zu erlernen. Daraus können Ruckschlüsse auf neue Materialpaarungen gezogen werden. So kann bei der Planung von neuen Produkten mit variierenden Materialeigenschaften und -geometrien auf kostspielige Experimente, zur Ermittlung der Schweißparameter, verzichtet werden.

Im größeren Kontext lassen sich so in der LaiLa Modellfabrik für jeden Produktionsschritt Repräsentationen in neuronalen Netzen erlernen, welche eine Vorhersage von Eingabedaten, Ausgabedaten und Parametrisierung ermöglichen.

B. Konzept

Das Erlernen von Repräsentationen von Prozessschritten basiert auf der Annahme, dass es sich bei Produktionsprozessen um Funktionen handelt, welche eine Eingabe unter dem Einfluss von Umgebungsvariablen in eine Ausgabe transformieren (s. Abbildung 5) [16]. Jeder Prozessschritt stellt hierbei ein eigenständiges Differenzialgleichungssystem dar und wird von einem eigenen neuronalen Netz erlernt. Anhand dieser Netzwerke können Vorhersagen über Ein- und Ausgaben, sowie die Prozessschrittparametrisierung getroffen werden.

In einem weiteren Schritt werden die einzeln angelernten Netzwerke zu einem Graphen zusammengefasst. Basierend auf dieser Struktur lassen sich Pfade durch den Graphen erzeugen, die basierend auf Ein- und Ausgangsdaten, eine Abfolge von Produktionsschritten mit entsprechender Parametrisierung, einen Plan, erzeugen.

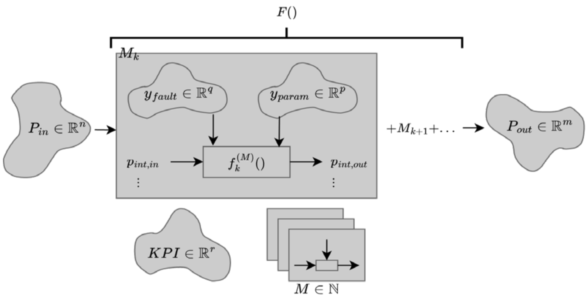


ABBILDUNG 5: FORMALISIERUNG EINES PRODUKTIONSPROZESSES INNERHALB EINES PRODUKTIONSSYSTEMS. DER PRODUKTIONSPROZESS $F()$ BESTEHT AUS k PROZESSSCHRITTEN $f^M()$ UND TRANSFORMIERT EINGABEN p_{in} IN AUSGABEN p_{out} UNTER BERÜCKSICHTIGUNG VON UMGEBUNGS-, PARAMETRISIERUNGS-, UND FEHLERVARIABLEN y_{fault} UND y_{param} [16].

Das vorgeschlagene Konzept kann mithilfe der Daten aus dem Use Case Ultraschallschweißen und der Modellfabrik validiert werden. Generalisierungen auf andere Produktionssysteme, auch aus der Verfahrenstechnik, sind möglich.

VI. ZUSAMMENFASSUNG

Zusammenfassend kann festgehalten werden, dass die im Projekt LaiLa verfolgte Umsetzung der Modellfabrik, welche einen Herstellungsprozess eines Wasserstofftanks abbildet, einen erheblichen Einfluss auf die Datengenerierung und -verarbeitung hat. Die dort erzeugten Daten sind realitäts- sowie industrienah und bieten die Möglichkeit unterschiedlichste Verfahren zu erforschen, zu validieren und zu evaluieren.

Hierunter fallen ebenso verschiedene Ansätze aus KI und ML. Mit der Überarbeitung der Infrastruktur auf Systemebene sollen Daten für alle internen Mitarbeiter zugänglich und nutzbar sein. So kann die Forschung in Bezug auf die Digitalisierung stetig vorangetrieben werden.

Derzeit werden Themen aus den Bereichen RL, Generative Modelle sowie Repräsentationslernen erforscht, welche zukünftig in unterschiedlichen industriellen Anwendungen implementiert werden können. Da der konstruierte Wasserstofftank viele verschiedene Herstellungsprozesse abbildet, bietet sich die Modellfabrik auch für Anwendungen in den Bereichen Fertigungstechnik und Automatisierung an.

VII. AUSBLICK

Zukünftig werden die oben vorgestellten Konzepte vertieft und auf Detailebene dokumentiert. Die Umsetzung der einzelnen Bausteine wird zunächst auf Grundlage von Simulationen stattfinden, bis sie an Realsystemen validiert und getestet werden können. Weiterhin wird nach Anwendungsfeldern für die Forschung gesucht, welche ebenso mit der Infrastruktur der Modellfabrik angegangen werden können.

DANKSAGUNG

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt LaiLa]

LITERATUR

[1] N. Widulle, J. Ehrhardt, M. Krantz, A. Liebert, A. Nordhausen, and O. Niggemann, *Eine Simulationsumgebung für flexible Cyber-Physische Produktionssysteme zur Generierung realistischer Datensätze für maschinelle Lernverfahren*, ser. Automation 2022: Automation creates Sustainability. Dusseldorf: VDI Verlag, 24.08.2022 2022, pp. 439–452. [Online]. Available: https://doi.org/10.51202/9783181023990-533

[2] C. Hildebrandt, T. Reincke, A. Fay, O. Niggemann, and M. Fette, "Wissenstransfer für die intelligente fabrik," *maschinenbau*, 2022.

[3] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction*. Cambridge, MA, USA: A Bradford Book, 2018.

[4] Laboratorium Fertigungstechnik, Helmut-Schmidt-Universität LaFT Universität der Bundeswehr, "Laila - labor für intelligente leichtbau-produktion," 06.

[5] P. Michalski, "Anomaly detection in the context of reinforcement learning," 08 2021.

[6] G. Pang, A. Hengel, C. Shen, and L. Cao, "Deep reinforcement learning for unknown anomaly detection," 09 2020.

[7] R. Sali, S. Adewole, and A. Akakpo, "Feature selection using reinforcement learning," 01 2021.

[8] S. M. Hazrati Fard, A. Hamzeh, and S. Hashemi, "Using reinforcement learning to find an optimal set of features," *Computers Mathematics with Applications*, vol. 66, pp. 1892–1904, 12 2013.

[9] H. Jomaa, J. Grabocka, and L. Schmidt-Thieme, "Hyp-rl: Hyperparameter optimization by reinforcement learning," 06 2019.

[10] S. C. Wong, A. Gatt, V. Stamatescu, and M. D. McDonnell, "Understanding data augmentation for classification: When to warp?" in *2016 International Conference on Digital Image Computing: Techniques and Applications (DICTA)*. IEEE, nov 2016.

[11] I. J. Goodfellow, "Nips tutorial generative adversarial networks," *CoRR*, vol. abs/1701.00160, 2017. [Online]. Available: http://arxiv.org/abs/1701.00160

[12] Y. Bengio, A. Courville, and P. Vincent, "Representation learning: A review and new perspectives," *IEEE transactions on pattern analysis and machine intelligence*, vol. 35, no. 8, pp. 1798–1828, 2013.

[13] D. Kiran, *Production planning and control: A comprehensive approach*.
Butterworth-heinemann, 2019.

[14] A. Kocher, R. Heesch, N. Widulle, A. Nordhausen, J. Putzke, A. Wind- ¨ mann, and O. Niggemann, "A Research Agenda for AI Planning in the Field of Flexible Production Systems," in *IEEE International Conference on Industrial Cyber-Physical Systems (ICPS)*, 2022.

[15] R. Heesch, N. Widulle, A. Kocher, A. Nordhausen, L. M. Vieira da Silva,¨ J. Putzke, and O. Niggemann, *Methoden der künstlichen Intelligenz für die automatisierte Planung von modularen Produktionsprozessen*, ser. Automation 2022: Automation creates Sustainability. Düsseldorf: VDI Verlag, 24.08.2022 2022, pp. 439–452. [Online]. Available: https://doi.org/10.51202/9783181023990-439

[16] J. Ehrhardt, M. Ramonat, R. Heesch, K. Balzereit, A. Diedrich, and O. Niggemann, "An ai benchmark for diagnosis, reconfiguration planning," in *2022 27th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA2022)*, 2022.

Interdisziplinäre Forschungsperspektiven auf die Digitalisierung in der Leichtbauproduktion und Anwendungsmöglichkeiten in der LaiLa Modellfabrik

Vincent Adomat*, Maryam Ahanpanjeh, Christian Kober, Marc Fette, Jens P. Wulfsberg
Institute of Production Engineering
Helmut Schmidt University / University of the Federal Armed Forces Hamburg
Hamburg, Germany
*vincent.adomat@hsu-hh.de

***Zusammenfassung*—Die zentrale Idee von „LaiLa“ ist es, durch den Aufbau eines Digitalisierungslabors für intelligente Leichtbauproduktion am CTC einen in alle Richtungen wirkenden Wissenstransfer aus Grundlagenforschung, anwendungsnaher Forschung und Entwicklung sowie industrieller Anwendung in der Luftfahrt zu ermöglichen. Die Digitalisierung ist ein Mittel, um Nachhaltigkeit und Effizienz in der Produktion durch intelligente Vernetzung, automatisierte Produktionssysteme, Echtzeit-Abbildung, Überwachung und Steuerung sowie flexibles Produktionsdesign zu erreichen. In diesem Beitrag wird erläutert, inwiefern energieoptimierte Produktionsplanung und -steuerung in der Compositeverarbeitung, robotergestütztes kontinuierliches Ultraschallschweißen und Digitale Zwillinge im Rahmen der Modellfabrik getestet und erforscht werden können, um Qualität zu steigern, individualisierte Fertigung zu ermöglichen und Ressourceneffizienz und Transparenz zu erhöhen.**

***Index Terms*—Digitalisierung, Leichtbauproduktion, Produktionsplanung, Ultraschallschweißen, Digitale Zwillinge, Nachhaltigkeit**

I. Einleitung

Leichtbaustrukturen aus Faserverbundkunststoffen (FVK) leisten heute einen wesentlichen Beitrag, Flugzeuge leichter und treibstoffsparender zu machen. Die Herstellung von FVK-Teilen ist jedoch aufgrund des Designs und der Komplexität der Fertigungsprozesse sehr aufwändig. Die Herausforderung besteht gleichzeitig darin, durch Automatisierung und Digitalisierung die heutigen Prozesse besonders in der Serienproduktion wesentlich effizienter zu gestalten [1].

Das Projekt „LaiLa“ ist ein durch das Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr (dtec.bw) getragenes Projekt. Die digitale Entwicklung der Leichtbauproduktion in der Luftfahrtindustrie steht hierbei im Fokus. Das Produktionsumfeld im Faserverbundleichtbau zeichnet sich durch einen hohen Anteil manueller Tätigkeiten bei gleichzeitig hoher Variantenvielfalt mit höchsten Qualitätsansprüchen aus. Dieses Umfeld ist stark von Expertenwissen und der individuellen Verfügbarkeit des Personals abhängig. Darüber hinaus sind qualitätsrelevante Prozesse nicht digital verfügbar, was in späteren Lebenszyklusphasen, u.a. im Rahmen der Produktion oder im Betrieb, zu erheblichem Mehraufwand führt. Ziel des Projektes ist, zu erforschen, wie die Produktion nachhaltiger und verbessert gestaltet werden kann, insbesondere im Hinblick auf die Qualität und Robustheit der Prozesse. Es wird angestrebt, Schnittstellen zwischen physischer Produktion, Qualitätssicherung, digitalen Modellen, Simulationen und Maschinellem Lernen (ML) herzustellen. Der Aufbau eines Labors für intelligente Leichtbauproduktion soll einen in alle Richtungen wirkenden Wissenstransfer zwischen Grundlagenforschung, anwendungsnaher Forschung und Entwicklung sowie industrieller Anwendung in der Luftfahrt ermöglichen [2].

Im Rahmen von LaiLa soll der Produktionsprozess durch Digitalisierung in Form modellierter, vernetzter und durch Künstliche Intelligenz (KI) und Maschinelles Lernen (ML) unterstützter Produktionssysteme wesentlich effizienter gestaltet werden. Die zentrale Idee von LaiLa ist es, durch den Aufbau eines Labors für intelligente Leichtbauproduktion einen in alle Richtungen wirkenden Wissenstransfer aus Grundlagenforschung, anwendungsnaher Forschung und Entwicklung sowie industrieller Anwendung in der Luftfahrt zu ermöglichen [1], [3]. Durch Expertenwissen werden somit gezielt innovative Schlüsseltechnologien in heutige und zukünftige Produktionssysteme gebracht. Dazu ist es notwendig, Domänenwissen digital zu modellieren und in einem datenbasierten Digitalen Zwilling (DT) abzubilden. Aufbauend auf Serienanlagen und vernetzten Maschinen wird das Konzept der intelligenten Fabrik mit allen Schnittstellenfunktionen demonstriert und validiert. Darüber hinaus dient das im Projekt aufgebaute Labor als interdisziplinäre Plattform für Weiterbildung und Wissenstransfer [4].

Die Laborplattform wird am Composite Technology Center / CTC GmbH, dem Leichtbau-Technologie- und Innovationszentrum von Airbus in Deutschland, als zentraler Technologieinkubator geschaffen und dient als industrienahe Entwicklungs- und Validierungsplattform für alle Arbeitspakete und die im Projekt abgebildeten Anwendungsbereiche, sogenannten 'Use Cases'. Drei dieser Use Cases werden im

https://doi.org/10.24405/14557

Folgenden bezüglich der wissenschaftlichen sowie industriellen Relevanz vorgestellt und das damit einhergehende systematische Vorgehen im Projekt erläutert.

II. Energieoptimierte Produktionsplanung und -steuerung in der Compositeverarbeitung

Die Bekämpfung des Klimawandels und seiner Folgen ist eines der zentralen Probleme dieser Zeit. Auf der UN Climate Change Conference 2021 in Glasgow hat sich die Weltgemeinschaft erneut dem Ziel einer Erderwärmung von nicht mehr als 1,5 °C verschrieben [5]. Aus diesen Bemühungen resultieren Leitlinien zur Reduktion und Vermeidung von Treibhausgasen sowohl auf europäischer, als auch auf nationaler Ebene. Das wichtigste Rahmenwerk stellt dabei der Green Deal der Europäischen Union dar, der sicherstellen soll, dass Europa bis zum Jahr 2050 vollständig klimaneutral wird [6]. Um auch zukünftig einem wachsendem Mobilitätsbedürfnis gerecht werden zu können, bedarf es aus diesem Grund drastischer Veränderungen in allen Bereichen des kommerziellen zivilen Luftfahrtsektors. Nicht nur ist es unerlässlich, dass Flugzeuge in Zukunft mit klimaneutralen Antrieben fliegen, sondern auch, dass diese klimaneutral produziert werden können.

Compositewerkstoffe sind bereits heute einer der wichtigsten Treiber der Effizienzsteigerung im Bereich Luftfahrt. Neben der Gewichtsreduktion und damit einhergehender Ressourceneinsparung während des Betriebs benennt der Branchenverband Composite United e.V. eine ganze Reihe weiterer Vorteile von sogenannten FVKs. So ist für die Herstellung ihrer Ausgangsmaterialien weniger Energie erforderlich als für metallische Werkstoffe und insbesondere kohlefaserbasierte Composites können aus pflanzlichem Material oder Luft-CO_2 hergestellt werden und so als CO_2 Senke dienen. Zudem sind heute mehrere Möglichkeiten der Nachnutzung und Verwertung, bis hin zum vollständigen Recycling, in Verwendung oder industrieller Erprobung [7].

Nicht nur im Bereich der kommerziellen Luftfahrt sind Leichtbautechnologien aus diesen Gründen für eine klimaneutrale Mobilität unverzichtbar. Neben den beschriebenen Vorteilen ihrer Verwendung existieren für die Unternehmen der Composite Herstellung und Verarbeitung jedoch noch ein breites Spektrum an Herausforderungen, um Composites auch in weiteren Bereichen marktfähig zu machen und in etablierten auch bei steigenden Energiepreisen marktfähig zu halten. Bereits heute lässt sich die gesamte Prozesskette der Composite Herstellung in industriellem Maßstab elektrifizieren. Dies stellt eine wichtige Voraussetzung der Dekarbonisierung industrieller Verarbeitung dar. Etablierte Verfahren können weiter genutzt werden. Branchenübergreifend spielen kurzfristig schwankende Energiepreise heute in vielen Industrien eine untergeordnete Rolle [8]. Die aus schwankenden Preisen resultierende Unsicherheit wird in aller Regel mit langfristigen Lieferverträgen oder Beteiligungen an linearen Lieferanten (Kohle-, Gas oder Atomkraftwerke) monetär kompensiert und somit auf andere Marktteilnehmer verlagert. Während durchschnittliche Preise für elektrische Energie zukünftig weiter zulegen dürften [9], bietet das wachsende Angebot an erneuerbarer elektrischer Energie in Kombination mit dem liberalisierten europäischen Strommarkt [10] jedoch auch Chancen für all jene, die in der Lage sind ihren Bedarf dynamisch an das bestehende Angebot anzupassen.

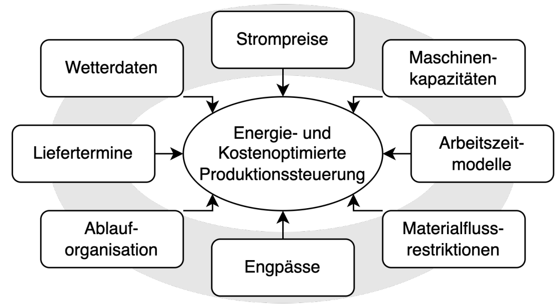


Abbildung 1. Relevante Perspektiven einer energieoptimierten Produktionsplanung und -steuerung

Im Rahmen des dtec Labors für intelligente Leichtbauproduktion (LaiLa) der Helmut-Schmidt-Universität und des Composite Technology Centers (CTC GmbH, an Airbus Company) in Stade wird aus diesem Grund unter anderem erforscht, wie moderne Produktionsplanung und -steuerung in Unternehmen der Compositeverarbeitung mittels digital vernetzter Produktionsanlagen um die Perspektive „Energiebedarf und Energiekosten“ erweitert werden kann. Die Ergebnisse versetzen Betriebe unterschiedlicher Größe in die Lage energie- und arbeitsintensive Prozesse eindeutig zu identifizieren und ablauforganisatorisch zu entkoppeln. In Kombination mit Methoden der Strompreisvorhersage [11] wird die Möglichkeit geschaffen, im Rahmen einer dynamischen Planung energieintensive Prozesse dynamisch zeitlich zu verlagern und kostenoptimal mit bestehenden Arbeitszeitmodellen in Einklang zu bringen. In der Compositeverarbeitung klassische Autoklav-basierte Fertigungsverfahren können dabei gleichermaßen hinsichtlich Kosten und CO_2-Rucksack optimiert werden, wie moderne „out of autoclave“ Verfahren. Der energieintensive, aber vergleichsweise arbeitsarme, gemeinsame zentrale Aspekt dieser Technologien ist dabei die Härtung eines Matrix-Kunststoffs mittels Wärme und Druck [12]. Umgekehrt ist die vorhergehende Herstellung von Rohgelegen oder Vakuumaufbauten arbeitsintensiver und benötigt aber deutlich weniger Energie. Eine energieoptimierte Produktionsplanung und -steuerung für die Compositeverarbeitung muss eine Vielzahl von Faktoren berücksichtigen. Zu den Perspektiven der aktuellen sowie prognostizierten Energieverfügbarkeit und Energiekosten kommen klassische Merkmale der Planung und Steuerung wie eine Engpassbetrachtung oder die Verfügbarkeit qualifizierten Personals hinzu. Figure 2 stellt die wichtigsten Planungsperspektiven der energieoptimierten Steuerung dar.

Neben der theoretischen Entwicklung des oben beschriebenen Systems der Produktionsplanung und -steuerung erfolgt auch dessen Erprobung im industriellen Kontext.

Die praxisnahe Erprobung der gewonnenen Erkenntnisse erfolgt anhand der im Rahmen des Labors für intelligente Leichtbauproduktion entstehenden Modellfabrik am Composite Technology Centers. Hier können quantitative Optimierungsmodelle der Produktionsplanung und -steuerung unter realistischen Bedingungen in einem industriellen Umfeld untersucht werden. Auf Basis realer Produktionsdaten der Modellfabrik wird eine simulative Erprobung einer solchen Implementierung der Planung und Steuerung möglich. Die im Rahmen von LaiLa entwickelte Architektur ist somit entlang der Bedürfnisse industrieller Compositeverarbeitung entwickelt. LaiLa stellt eine einzigartige Plattform dar, mittels derer eine unmittelbare Applizierung wissenschaftlicher Erkenntnisse im industriellen Kontext möglich wird.

Die Erforschung der energieoptimierten Produktionsplanung und -steuerung im Rahmen von LaiLa legt einen wichtigen Grundstein zur Dekarbonisierung der luftfahrtspezifischen Wertschöpfungskette der Compositverarbeitung. Durch die einmalige Kombination von industrieller Erprobung und wissenschaftlicher Methodik wird gleichermaßen eine direkte industrielle Applizierbarkeit und eine hohe Zugänglichkeit sowie eine starke Generalisierbarkeit der erlangten Erkenntnisse ermöglicht. Industrielle Bemühungen zur Eliminierung von Treibhausgasen werden unter Wahrung der internationalen Wettbewerbsfähigkeit branchenübergreifend gestärkt.

ABBILDUNG 2. 6-ACHS-ROBOTER FÜR DAS ULTRASCHALLSCHWEISSEN AM CTC

III. DAS ROBOTERGESTÜTZTE KONTINUIERLICHE ULTRASCHALLSCHWEISSEN

In den letzten Jahren hat die Nachhaltigkeit eine zunehmende Bedeutung in der Industrie gewonnen, welche zu einem zunehmenden Einsatz von carbonfaserverstärktem Kunststoff (CFK) in der Luftfahrt seit den 1960er-Jahren führt. Neben den ökonomischen und ökologischen Vorteilen verfügen CFK Materialien über eine hohe Steifigkeit und Festigkeit der Faser bei vergleichbar geringer Dichte. Unter CFK Materialien setzen sich faserverstärkte Thermoplaste aus vielen Gründen steigend in der Luft- und Raumfahrtindustrie durch, wie zum Beispiel einfache Herstellung, hohe Materialzähigkeit und Recyclingfähigkeit [13]. Der Einsatz von Leichtbaumaterialien erfordert von Industrieunternehmen eine Anpassung ihrer Fertigungsstrategien. Das Ultraschallschweißen (US) als eines der vielversprechendsten Fügeverfahren für thermoplastische Verbundwerkstoffe hat aufgrund seiner Vorteile wie hohe Festigkeit, hohe Energieeffizienz, kurze Verarbeitungszeit und vollständige Automatisierung große Aufmerksamkeit bei Luftfahrtindustrie erfahren, welches herkömmliche mechanische Befestigungstechniken ersetzen kann [14]–[16]. Diese Technologie wird von Airbus für die Integration von Profilen und das Schließen von langen Nähten betrachtet. Trotz der zahlreichen Vorteile des Ultraschallschweißens wurde es bisher nicht industriell zum Fügen von thermoplastischen Bauteilen eingesetzt [14]. Der Ultraschallschweißprozess besteht im Wesentlichen aus einer Vibrationsphase und einer Konsolidierungsphase [14] und basiert auf Reibungs- und Viskoelastische Wärme, welche durch die Umwandlung von (hoch Frequenz-niedrig Amplitude) Ultraschallschwingungen in mechanische Schwingungen in der Vibrationsphase erzeugt und durch die Sonotrode in die zu schweißenden Bauteile eingeleitet wird [17]–[19]. Während der Konsolidierungsphase wird die Schweißnaht unter dem Druck von der Konsolidierungseinheit unter die Glasübergangstemperatur (Tg) von Matrix abgekühlt [14]. Die primären Prozessparameter beim kontinuierlichen Ultraschallschweißen sind die Amplitude, die Frequenz (kein freier Parameter), der Schweiß- und Konsolidierungskraft und die Geschwindigkeit [19], [20].

Es gibt zwei Arten von Ultraschallschweißen: I) statisch, II) kontinuierlich [15], [16]. Beim statischen Ultraschallschweißen kann der Prozess durch die Leistung des Generators und vertikale Verschiebung der Sonotrode während des Prozesses überwacht und gesteuert werden [15], [17], [21]. Beim Kontinuierlichen ist hingegen die Steuerung und Überwachung des Prozesses sehr herausfordernd. US kann sowohl durch eine Schweißmaschine als auch einen Industrieroboter durchgeführt werden. Industrieroboter bieten eine wirtschaftliche und flexible Bearbeitungsalternative und eignen sich für das Schweißen der komplexen Bauteile. Sie besitzen jedoch wegen der geringeren Steifigkeit keine hohe Absolut- und Wiederholgenauigkeit, während die Schweißmaschinen dank deren kartesisch unabhängiger Achsen und hohen Achsen-Steifigkeit genaue Ergebnisse erzielen. Die Genauigkeit der Roboter hängt stark von der Pose ab. Das bedeutet, dass die Roboter in der Mitte des Arbeitsbereichs genauer sind als im Randbereich, wo die Arme ausgestreckt sind. Das kann beim Schweißen großer Bauteile in der Luftfahrtindustrie zu Problemen führen. Neben der Steifigkeit gibt es mehrere Faktoren, die die Positions- und Bahngenauigkeit beeinflussen, wie z. B. Temperatur, Frequenz, elastische Verformung des Endeffektors usw. Die Robotergenauigkeit lässt insbesondere unter Prozesskraftbelastung nach. Die aufgebrachten Prozesskräfte wirken als zusätzliche Störgröße und beeinflussen die Robotergenauigkeit. Um die hohen Ansprüche an Fertigungstoleranzen und angeforderte Reproduzierbarkeit in der Luftfahrt gewährleisten zu können, müssen die Ursachen für eine fehlerhafte Schweißbahn, welche durch die falsche Auswahl von Prozessparametern sowie durch ein nicht optimales Führen des Endeffektors entlang der Schweißnaht hervorgerufen werden, ermittelt und beseitigt bzw. kompensiert werden. Außerdem müssen wichtige Kriterien und Anforderungen an die Schweißqualität berücksichtigt und gewährleistet werden. Dies erfordert den Erwerb entsprechender Kenntnisse über den US-Prozess, das Roboterverhalten und die Prozess-Maschine Interaktion. In der Prozess-Maschinen-Interaktion werden die Zusammenhänge zwischen den auf die Roboterauslenkung wirkenden Kräften und Momenten und den Schweißparametern sowie Geschwindigkeit, Schweißkraft, Konsolidierungskraft, etc. ermittelt, um geeignete Strategien zur Erzielung einer hohen Qualität und Präzision der Schweißbahn zu entwickeln. Das Ziel dieser Forschungsarbeit im Rahmen des LaiLa-Projektes ist die Erstellung einer automatisierten Schweißbahn beim robotergeführten kontinuierlichen Ultraschallschweißen mittels sensorgestützter Bewegungsausführung und Bewegungsbeobachtung. Dazu müssen die Einflussfaktoren auf die Schweißbahngenauigkeit und deren Kenngrößen durch die Implementierung geeigneter Messkonzepte erfasst werden. Anhand der Darstellung einer Erklärungskette und Sensitivitätsanalyse werden funktionale Zusammenhänge zwischen den Einflussfaktoren und der Schweißbahngenauigkeit ermittelt und mithilfe von Kompensationsstrategien und zahlreichen Optimierungsschritten in der Robotersteuerung die Abweichungen korrigiert.

Das LaiLa-Projekt ist ein intelligentes Leichtbau-Produktionslabor, welches als Validierungsplattform für diverse Technologien dient. Das Demoprodukt besteht aus einer konvexen, gepressten thermoplastischen Schale mit daran befestigten Stringern, wie sie im Flugzeugbau üblich sind. Diese Arbeit wird evaluiert, indem thermoplastische Omega-Stringer an die thermoplastische Schale geschweißt wird.

IV. Nutzen von Digitalen Zwillingen in Produktionsunternehmen

Die industrielle Fertigung wird immer individueller und komplexer. Unternehmen müssen agiler werden, um die sich ändernden Kundenbedürfnisse schneller und besser zu erfüllen. In der heutigen globalisierten Wirtschaft stehen sie unter ständigem Druck, ihre Leistung zu verbessern. Eine Möglichkeit, der steigenden Wettbewerbsfähigkeit zu begegnen, ist die Digitalisierung. Im Kontext von Smart Factory und Industrie 4.0 gibt es ein breites Spektrum an Technologien, die zu diesem Zweck eingesetzt werden können [22]–[24].

Eines der vielversprechenden Konzepte ist der Digitale Zwilling (DT). In den letzten Jahren ist die Zahl der wissenschaftlichen Veröffentlichungen zu diesem Thema exponentiell gestiegen [25]–[27]. Gleichzeitig starten viele Unternehmen, insbesondere große Konzerne, Initiativen, um das Potenzial von DTs zu erforschen [28]–[31].

Trotz dieser Aufmerksamkeit bleibt die Definition von DT umstritten. Die große Anzahl von Veröffentlichungen hat zu einer Vielzahl von Definitionen geführt, die jeweils ihre eigenen Besonderheiten aufweisen [32]–[35]. Ihr Verständnis unterscheidet sich je nach Branche, Anwendungsfall und Kontext erheblich. Die am meisten akzeptierten Definitionen stammen von [36], der das Konzept des Digitalen Zwillings zuerst eingeführt hat, und [37].

Grieves [36]:

> *“The Digital Twin concept model [...] contains three main parts: a) physical products in Real Space, b) virtual products in Virtual Space, and c) the connections of data and information that ties the virtual and real products together.”*

NASA [37]:

> *“A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems, including airframe, propulsion and energy storage, life support, avionics, thermal protection, etc.”*

Nach [32] umfassen die grundlegenden Elemente, die eine DT charakterisieren, eine physische Realität, ihre virtuelle Darstellung und einen bidirektionalen Datenaustausch. Der Begriff DT wird häufig verwendet, um von dem Hype um das Konzept zu profitieren [38]. Behauptete Implementierungen sind oft nur digitale Modelle (DM) oder digitale Schatten (DS), die nach [34] lediglich Unterkategorien von DTs darstellen, siehe FIGURE 3. Obwohl es bereits Demonstratoren im Labormaßstab gibt, hat das Konzept noch kaum die industrielle Praxis erreicht [39]. Echte DTs, wie sie von [34] definiert werden, sind rar. Die Ursachen hierfür sind vielfältig und komplex.

Es gibt mehrere Studien, die sich mit einigen der Hürden befasst haben, warum DTs bisher wenig verbreitet sind in der industriellen Praxis. In [40] wurden fünf zentrale Herausforderungen beim Aufbau von DTs identifiziert, wobei der Schwerpunkt ausschließlich auf technischen Aspekten lag. In [41], [42] und [43] wurden ebenfalls hauptsächlich tech-

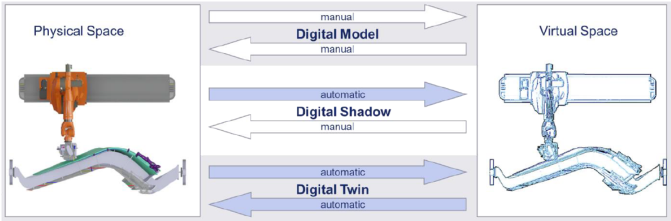


ABBILDUNG 3. SUBTYPEN DES DIGITALEN ZWILLINGS NACH [34]

nische Aspekte hervorgehoben. In [44] wurden gemeinsame Herausforderungen von DTs mit künstlicher Intelligenz (KI) und dem Internet der Dinge (IoT) in Smart Cities, in der Fertigung und im Gesundheitswesen beschrieben. [45] hat anhand einer Literaturübersicht fünf allgemeine Hauptherausforderungen bei der Anwendung von DTs in den Bereichen Smart Cities, Logistik, Medizin, Maschinenbau und Automobilbau herausgearbeitet. [46] führte eine systematische Literaturrecherche durch, um technische, soziale und kommerzielle Herausforderungen zu identifizieren. In [47] wurden virtuelle Modellierung, Unternehmensstruktur und Echtzeitdaten als zentrale Herausforderungen erkannt. [48] hat die DT-Herausforderungen bei der Entwicklung und Implementierung in der Fertigung hochwertiger Bauteile analysiert. Sie haben elf Schlüsselherausforderungen extrahiert, die unter fünf Themen gruppiert sind, wie z.B. Technik, Technologie und Daten. In [49] wurden die DT-Herausforderungen bei der Produktentwicklung und -produktion für hochleistungsfähige Teile hervorgehoben, wie die Integration verschiedener technischer Bereiche, die Standardisierung von Schnittstellen für den Datenaustausch und die effiziente Gestaltung des Informationsflusses.

In [50] wurden 15 Herausforderungen aus 3 Hauptbereichen identifiziert, die der flächendeckenden Anwendung von DTs entgegenstehen: technisch, organisatorisch und methodisch. Insbesondere die organisatorischen und methodischen Hürden werden vielfach unterschätzt. Hervorzuheben sind hier die Aspekte Akzeptanz der Mitarbeiter gegenüber der Digitalen Transformation, Unternehmenskultur sowie die Unsicherheit bezüglich einmaliger und laufender Kosten.

Darüber hinaus ist der Mehrwert von DTs in der Regel unklar und nicht greifbar [23], [26], [32], [51]. Dies verhindert eine unvoreingenommene Bewertung von Investitionen in DT-Technologien und führt zu einem Mangel an Akzeptanz innerhalb von Organisationen. Wenn Organisationen dennoch bereit sind zu investieren, führen sie diese Technologie oft als Selbstzweck ein, ohne eine über die Demonstration hinausgehende Strategie zu verfolgen. Einer der Gründe, warum der wirtschaftliche Nutzen von DTs schwer zu erfassen ist, liegt darin, dass die sogenannte Fidelity nicht ausreichend berücksichtigt wird [24]. Nach [26] gibt die Fidelity "die Anzahl der Parameter, ihre Genauigkeit und den Abstraktionsgradän, in der die virtuelle Abbildung das physische Pendant spiegelt. In Übereinstimmung mit den meisten akademischen Definitionen wird davon ausgegangen, dass DTs die physische Welt so realistisch wie möglich, d.h. in hoher Fidelity, abbilden müssen [37], [52]. Dabei profitiert der DT vom rasanten technologischen Fortschritt eng verwandter Technologien wie Simulation, Internet of Things (IoT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI) und Big Data [22], [25], [53]. In der Praxis konzentrieren sich Unternehmen jedoch darauf, Verbesserungen mit minimalem Aufwand zu erzielen. Daher ist es fraglich, ob es zwingend erforderlich ist, allumfassende DTs in hoher Fidelity zu erstellen [24], [26]. Bei der Simulation, einem Kernelement der DTs [27], [54], wird die Konzentration auf relevante Systemelemente gegenüber der Abbildung sämtlicher Eigenschaften, Verhaltensweisen und Zustände bevorzugt [55], [56]. Tatsächlich ist eine geringere Abbildungstreue gleichbedeutend mit geringeren Kosten im Vergleich zu einer hohen Abbildungstreue [57]. In [24] wurde daher eine Methode vorgeschlagen, die bei der Ausarbeitung geeigneter Fidelity Niveaus hilft und dadurch die Herausforderungen der Implementierungskomplexität überwindet und somit die Chancen für eine erfolgreiche Anwendung von DTs erhöht.

Um abschließend eine umfassende Bewertung des DTs zu ermöglichen, ist ein homogenes Basisverständnis notwendig. Momentan ist das Verständnis, was ein DT genau ist, sehr heterogen. Je nachdem, welche Person man befragt, unterscheidet sich die Antwort. Branche, Hierarchieebene, Funktion als auch der spezielle Anwendungsfall spielen hierbei eine Rolle. Für die Erarbeitung einer ganzheitlichen, wissenschaftlich fundierten sowie systeamtischen Vorgehensweise zur erfolgsversprechenden Einführung von Digitalen Zwillingen bildet die gemeinsame Kommunikationsgrundlage bezüglich der Definition und damit verbundener Erwartungshaltungen ein zwigend nötiges Fundament.

Im Rahmen LaiLa kann eine solche systematische und praxistaugliche Methodik zur erfolgversprechenden Anwendung von DTs validiert werden. Die Modellfabrik eignet sich hierfür besonders als Plattform. Hier können diverse Szenarien sowohl fiktiv als auch real durchgespielt werden, in denen unterschiedliche DTs für unterschiedliche Zielsetzungen eingesetzt werden. Diese Szenarien können dann entsprechend vorher festgelegter Kennzahlen miteinander verglichen werden. Auf dieser Basis kann überprüft werden, inwiefern ein systematisches Vorgehen mithilfe der in LaiLa entwickelten Methodik zu besseren Entscheidungen führt. Es kann u.a. untersucht werden, inwiefern sich unterschiedliche Fidelity Levels auf das Endergebnis, also den erzielten Mehrwert durch die Anwendung des DT, auswirken. Die Anforderungen an den DT werden dabei von Beginn an systematisch erhoben und auch im Nachgang überprüft.

V. ZUSAMMENFASSUNG UND AUSBLICK

Eine große Herausforderung des Luft- und Raumfahrtsektors heute und in Zukunft ist die Effizienzsteigerung und Flexibilisierung der Wertschöpfung, vor allem des gesamten Produktionssystems [58]. Durch ein physisches Labor im Rahmen des Projektvorhabens LaiLa werden industrielle Prozesse, Anlagen und Leichtbau-Produktionsbereiche der Luft-und Raumfahrtindustrie im Composite Technology Center / CTC GmbH nachgebildet und kollaborativ betrieben. Hierbei sollen die einheitliche Datenerfassung und -aufbereitung für eine automatisierte Produktions- und Produktüberwachung entsprechend der Konzepte von Industrie 4.0 vorangetrieben werden. Neben hochmodernen, industriellen Herangehensweisen werden Forschungsfortschritte aus dem wissenschaftlichen Bereich einbezogen, um so einen Wissenstransfer zwischen Grundlagenforschung, anwendungsnaher Forschung und Entwicklung sowie industrieller Anwendung fokussiert auf die Leichtbauproduktion zu generieren.

DANKSAGUNG

Das Projekt Interdisziplinäre Forschungsperspektiven auf die Digitalisierung in der Leichtbauproduktion und Anwendungsmöglichkeiten in der LaiLa Modellfabrik wird durch dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr gefördert. Die Autoren bedanken sich für die Förderung.

LITERATUR

[1] [Online]. Available: "https://dtecbw.de/home/forschung/hsu/projekt-laila"

[2] [Online]. Available: "https://de.industryarena.com/hsu-hh-laft/blog/laila-labor-fuer-intelligente-leichtbauproduktion--19576.html"

[3] [Online]. Available: "https://www.hsu-hh.de/laft/forschung/laila-labor-fuer-intelligente-leichtbauproduktion"

[4] C. Hildebrandt, T. Reincke, A. Fay, O. Niggemann, and M. Fette, "Wissenstransfer für die intelligente fabrik," *maschinenbau*, vol. 2, pp. 24–27, 06 2022.

[5] UN Conference of the Parties (CoP), "COP26 - The Glasgow Climate Pact," Nov. 2021. [Online]. Available: https://ukcop26.org/wp-content/uploads/2021/11/COP26-Presidency-Outcomes-The-Climate-Pact.pdf

[6] European Commission, "A European Green Deal," Dec. 2019. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[7] Composites United e. V., "Klimaneutralität durch innovativen Leichtbau," Nov. 2021. [Online]. Available: https://composites-united.com/wp-content/uploads/2021/11/Klimaneutralitaet-durch-innovativen-Leichtbau.pdf

[8] P. J. Burke and A. Abayasekara, "The Price Elasticity of Electricity Demand in the United States: A Three-Dimensional Analysis," *The Energy Journal*, vol. 39, no. 2, Apr. 2018. [Online]. Available: http://www.iaee.org/en/publications/ejarticle.aspx?id=3055

[9] Bundesnetzagentur, "SMARD - Strommarktdaten für Deutschland," Sep. 2022. [Online]. Available: https://www.smard.de/home/marktdaten

[10] The European Commission, "Electricity market design," Jan. 2022. [Online]. Available: https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/electricity-market-design_en

[11] H. Lu, X. Ma, M. Ma, and S. Zhu, "Energy price prediction using data-driven models: A decade review," *Computer Science Review*, vol. 39, p. 100356, Feb. 2021. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1574013720304561

[12] R. Harshe, "A Review on Advanced Out-of-Autoclave Composites Processing," *Journal of the Indian Institute of Science*, vol. 95, no. 3, pp. 207–220, Sep. 2015, number: 3. [Online]. Available: http://journal.iisc.ernet.in/index.php/iisc/article/view/4567

[13] M. Humer, "Diplomarbeit - charakterisierung von verbundwerkstoffen mit thermoplastischer matrix," p. 114.

[14] I. F. Villegas, "Strength development versus process data in ultrasonic welding of thermoplastic composites with flat energy directors and its application to the definition of optimum processing parameters," vol. 65, pp. 27–37. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1359835X14001614

[15] B. Jongbloed, J. Teuwen, R. Benedictus, and I. F. Villegas, "On differences and similarities between static and continuous ultrasonic welding of thermoplastic composites," vol. 203, p. 108466. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1359836820335149

[16] F. Köhler, B. Jongbloed, T. Filipe, A. Herrmann, I. F. Villegas, and R. Benedictus, "A roadmap for developing an industrial continuous ultrasonic welding process for thermoplastic composites," p. 5.

[17] I. F. Villegas, "In situ monitoring of ultrasonic welding of thermoplastic composites through power and displacement data," vol. 28, no. 1, pp. 66–85. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0892705712475015

[18] Zongbo Zhang, Xiaodong Wang, Yi Luo, Zhenqiang Zhang, and Liding Wang, "Study on heating process of ultrasonic welding for thermoplastics," vol. 23, no. 5, pp. 647–664. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0892705709356493

[19] A. Yousefpour, M. Hojjati, and J.-P. Immarigeon, "Fusion bonding/welding of thermoplastic composites," vol. 17, no. 4, pp. 303–341. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0892705704045187

[20] I. F. Villegas and G. Palardy, "Ultrasonic welding of thermoplastic composite coupons for mechanical characterization of welded joints through single lap shear testing," no. 108, p. 53592. [Online]. Available: http://www.jove.com/video/53592/ultrasonic-welding-thermoplastic-composite-coupons-for-mechanical

[21] F. Köhler, I. Villegas, C. Dransfeld, and A. Herrmann, "Static ultrasonic welding of carbon fibre unidirectional thermoplastic materials and the influence of heat generation and heat transfer," vol. 55, no. 15, pp. 2087–2102. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0021998320976818

[22] E. Oztemel and S. Gursev, "Literature review of Industry 4.0 and related technologies," *Journal of Intelligent Manufacturing*, vol. 31, no. 1, pp. 127–182, Jan. 2020. [Online]. Available: https://doi.org/10.1007/s10845-018-1433-8

[23] P. Osterrieder, L. Budde, and T. Friedli, "The smart factory as a key construct of industry 4.0: A systematic literature review," *International Journal of Production Economics*, vol. 221, p. 107476, Mar. 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0925527319302865

[24] C. Kober, V. Adomat, M. Ahanpanjeh, M. Fette, and J. Wulfsberg, "Digital Twin Fidelity Requirements Model For Manufacturing," in *Proceedings of the 3rd Conference on Production Systems and Logistics (CPSL)*, Vancouver, 2022, pp. 595–611.

[25] M. Liu, F. Shuiliang, H. Dong, and C. Xu, "Review of digital twin about concepts, technologies, and industrial applications," *Journal of Manufacturing Systems*, vol. 58, Jul. 2020.

[26] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the Digital Twin: A systematic literature review," *CIRP Journal of Manufacturing Science and Technology*, vol. 29, pp. 36–52, May 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1755581720300110

[27] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital Twin in Industry: State-of-the-Art," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 4, pp. 2405–2415, Apr. 2019, conference Name: IEEE Transactions on Industrial Informatics.

[28] M. Wendenburg, "Digital Twin is about to rollout by Airbus," Jul. 2017, section: Press. [Online]. Available: https://ascon-systems.de/en/digital-twin-is-about-to-rollout-by-airbus/

[29] Daimler, "Production is becoming smart. Industry 4.0 and the networked factory," section: Innovation. [Online]. Available: https://www.daimler.com/innovation/case/connectivity/industry-4-0.html

[30] B. Caulfield, "NVIDIA, BMW Blend Reality, Virtual Worlds to Demonstrate Factory of the Future," Apr. 2021. [Online]. Available: https://blogs.nvidia.com/blog/2021/04/13/nvidia-bmw-factory-future/

[31] G. Electric, "Digital Twin," Jan. 2022. [Online]. Available: https://www.ge.com/digital/applications/digital-twin

[32] E. VanDerHorn, "Digital Twin: Generalization, characterization and implementation," *Decision Support Systems*, p. 11, 2021.

[33] J.-F. Uhlenkamp, K. Hribernik, S. Wellsandt, and K.-D. Thoben, "Digital Twin Applications : A first systemization of their dimensions," Jun. 2019, pages: 8.

[34] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, "Digital Twin in manufacturing: A categorical literature review and classification," *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 1016–1022,

Jan. 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2405896318316021

[35] E. Negri, L. Fumagalli, and M. Macchi, "A Review of the Roles of Digital Twin in CPS-based Production Systems," *Procedia Manufacturing*, vol. 11, pp. 939–948, Jan. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2351978917304067

[36] M. Grieves, "Digital Twin: Manufacturing Excellence through Virtual Factory Replication," Mar. 2015.

[37] E. H. Glaessgen and D. S. Stargel, "The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles," Honolulu, HI, Apr. 2012, nTRS Author Affiliations: NASA Langley Research Center, Air Force Office of Scientific Research NTRS Report/Patent Number: NF1676L-13293 NTRS Document ID: 20120008178 NTRS Research Center: Langley Research Center (LaRC). [Online]. Available: https://ntrs.nasa.gov/citations/20120008178

[38] K. Panetta, "5 Trends Emerge In Gartner Hype Cycle For Emerging Technologies 2018," Nov. 2019. [Online]. Available: https://www.gartner.com/smarterwithgartner/5-trends-emerge-in-gartner-hype-cycle-for-emerging-technologies-2018

[39] D. Mourtzis, "Simulation in the design and operation of manufacturing systems: state of the art and new trends," *International Journal of Production Research*, vol. 58, no. 7, pp. 1927–1949, 2019. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00207543.2019.1636321

[40] W. Hu, T. Zhang, X. Deng, Z. Liu, and J. Tan, "Digital twin: a state-of-the-art review of its enabling technologies, applications and challenges," *Journal of Intelligent Manufacturing and Special Equipment*, vol. 2, no. 1, pp. 1–34, 2021, publisher: Emerald Publishing Limited. [Online]. Available: https://doi.org/10.1108/JIMSE-12-2020-010

[41] F. Bordeleau, B. Combemale, R. Eramo, M. Van Den Brand, and M. Wimmer, "Towards model-driven Digital Twin engineering: Current opportunities and future challenges," 2020.

[42] C. Semeraro, M. Lezoche, H. Panetto, and M. Dassisti, "Digital twin paradigm: A systematic literature review," *Computers in Industry*, vol. 130, 2021.

[43] J. Michael, "Integration Challenges for Digital Twin Systems-of-Systems," p. 4, 2022.

[44] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital Twin: Enabling Technologies, Challenges and Open Research," *IEEE Access*, vol. 8, pp. 108 952–108 971, 2020, conference Name: IEEE Access.

[45] D. M. Botín-Sanabria, A.-S. Mihaita, R. E. Peimbert-García, M. A. Ramírez-Moreno, R. A. Ramírez-Mendoza, and J. d. J. Lozoya-Santos, "Digital Twin technology challenges and applications: A comprehensive review," *Remote Sensing*, vol. 14, no. 6, p. 1335, 2022, number: 1335.

[46] T. Y. Melesse, V. D. Pasquale, and S. Riemma, "Digital Twin models in industrial operations: State-of-the-art and future research directions," *IET Collaborative Intelligent Manufacturing*, vol. 3, no. 1, pp. 37–47, 2021, _eprint: https://ietresearch.onlinelibrary.wiley.com/doi/pdf/10.1049/cim2.12010. [Online]. Available: https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/cim2.12010

[47] F. Pires, A. Cachada, J. Barbosa, A. P. Moreira, and P. Leitão, "Digital Twin in Industry 4.0: Technologies, Applications and Challenges," in *IEEE 17th International Conference on Industrial Informatics (INDIN)*, vol. 1, 2019, pp. 721–726, iSSN: 2378-363X.

[48] S. Singh, E. Shehab, N. Higgins, K. Fowler, T. Tomiyama, and C. Fowler, "Challenges of Digital Twin in High Value Manufacturing," in *SAE Technical Papers*, London, 2018, pp. 1–10.

[49] R. Wagner, B. Schleich, B. Haefner, A. Kuhnle, S. Wartzack, and G. Lanza, "Challenges and Potentials of Digital Twins and Industry 4.0 in Product Design and Production for High Performance Products," *Procedia CIRP*, vol. 84, pp. 88–93, Jan. 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827119308637

[50] C. Kober, M. Fette, and J. P. Wulfsberg, "Challenges of Digital Twin Application in Manufacturing," Kuala Lumpur, Dec. 2022.

[51] W. Polini and A. Corrado, "Digital twin of composite assembly manufacturing process," *International Journal of Production Research*, vol. 58, no. 17, pp. 5238–5252, Sep. 2020, publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00207543.2020.1714091. [Online]. Available: https://doi.org/10.1080/00207543.2020.1714091

[52] K. Reifsnider and P. Majumdar, "Multiphysics Stimulated Simulation Digital Twin Methods for Fleet Management," in *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, ser. Structures, Structural Dynamics, and Materials and Co-located Conferences. American Institute of Aeronautics and Astronautics, Apr. 2013. [Online]. Available: https://arc.aiaa.org/doi/10.2514/6.2013-1578

[53] F. Tao, Q. Qi, L. Wang, and A. Y. C. Nee, "Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison," *Engineering*, vol. 5, no. 4, pp. 653–661, Aug. 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S209580991830612X

[54] S. Boschert and R. Rosen, "Digital Twin—The Simulation Aspect," in *Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and their Designers*, P. Hehenberger and D. Bradley, Eds. Cham: Springer International Publishing, 2016, pp. 59–74. [Online]. Available: https://doi.org/10.1007/978-3-319-32156-1_5

[55] D.-J. van der Zee, "Model simplification in manufacturing simulation – Review and framework," *Computers & Industrial Engineering*, vol. 127, pp. 1056–1067, Jan. 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360835218305783

[56] P. Fishwick, "The role of process abstraction in simulation," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 18, no. 1, pp. 18–39, Jan. 1988, conference Name: IEEE Transactions on Systems, Man, and Cybernetics.

[57] R. Müller, M. Vette, L. Hörauf, C. Speicher, and D. Burkhard, "Lean Information and Communication Tool to Connect Shop and Top Floor in Small and Medium-sized Enterprises," *Procedia Manufacturing*, vol. 11, pp. 1043–1052, Dec. 2017.

[58] M. Fette and A. Herrmann, "Zivile luftfahrtindustrie im wandel der digitalisierung," *Sonderprojekte ATZ/MTZ*, vol. 22, pp. 38–41, 12 2017.

Current Trends in Robotics Development

Hamied Nabizada*, Marcel Lewke, Moein Azizpour, Raphael Höfer, Luis Miguel Vieira da Silva, Pezhman Pourabdollah, Philip Topalis, Omar Ismail, Alice Kirchheim, Alexander Fay
Institute of Automation Technology
Helmut Schmidt University / University of the Federal Armed Forces Hamburg
Hamburg, Germany
*hamied.nabizada@hsu-hh.de

***Abstract* – Nowadays, companies are facing several challenges, such as changing market demands and labor shortages. To cope with these challenges, the demand for the use of robots is steadily growing as robots are indispensable parts of industrial automation. Robots can increase productivity and quality for a specific application. This paper presents current trends in robotics that are being used and researched in different dtec.bw projects. In addition to the well-known industrial robots, lightweight and mobile robots are introduced and further trends are summarized.**

Keywords – Robotics, Industrial Robots, Lightweight Robots, Mobile Robotic, Unmanned Aerial Vehicles, Modular Robotics

I. Introduction

Robots typically help humans perform repetitive, dangerous or unergonomic tasks and have become an integral part of today's industrial environment [1]. Depending on the robot, they offer a range of advantages that a human being cannot provide to such an extent [2]. They can move with great speed and precision and perform their tasks with consistently high quality.

With today's challenges, such as the shortage of specialized workers and changing market demands, robotics is becoming an increasingly important factor influencing business success. This is where various research projects within the scope of the "Center for Digitization and Technology Research of the German Armed Forces" (dtec.bw) come in and attempt to facilitate the integration of robots in the industrial domain.

This paper intends to provide insights into the robotics trends being pursued in the involved dtec.bw research projects.

The paper is structured as follows. In the next section, current trends in robotics are described, which are examined in more detail in the dtec.bw research projects, and their advantages and disadvantages are discussed. The trends considered in this paper include established industrial robots, lightweight robots, and mobile robots. In addition, other trends that include drones and modular robotics are summarized. The paper concludes with a summary and outlook.

II. Current Trends in Robotics

The term "robot" originally comes from the Slavic word "robota" and means drudgery (forced labor). The term was created in 1920 by the theater play Rossum's Universal Robots by Josef Čapek, in which human-like figures take over human work and ultimately rebel against it [2]. According to ISO 8373:2021, the term robot is defined as "programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation or positioning" [3]. Within robotics, different disciplines have developed over time, and the category of industrial robots is discussed in the following subsection.

A. Standard Industrial Robots

Industrial robots represent a subfield of automation technology and, as universally programmable motion machines, enable the handling and processing of workpieces. Regarding kinematics, industrial robots can be divided into serial and parallel kinematics. In serial kinematics, the structure is serial, to an open kinematic chain. However, parallel kinematics involves a parallel, closed kinematic chain that couples axes of motion together. In the following, we will focus on serial kinematics, which is most represented in industrial robots.

The structure of an industrial robot consists of the manipulator (links and joints), which includes motors, gears, and sensors, the end effector, where various tools can be attached to the flange, and the controller to regulate the serial kinematics [4]. Figure 1 shows exemplary the industrial robot "KR 1000 titan" from the manufacturer KUKA.

Figure 1: KUKA KR 1000 titan as an example of industrial robots [5].

Industrial robots have made the development of many processes in the industry much more efficient. Industrial robots have developed significantly since the invention of the jointed-arm robot in the early 1950s and have steadily gained new applications since their first industrial use in 1961 with "Unimate 1900" [6]. They are most frequently used in

https://doi.org/10.24405/14558

production lines of the automotive industry, but they are also strongly represented in other industries such as the electronics industry. They support or perform various tasks such as joining, assembling, packaging, painting, measuring, grinding, cutting, milling, welding, etc. In most cases, the only difference between the robot systems is the end effector. The selection of different end effectors allows the robot to adjust to performing various tasks with different requirements.

The advantage of industrial robots is the high degree of automation, which combines high time utilization with consistent work quality, leading to increased efficiency. The high repeatability and flexibility are further advantages of industrial robots. Furthermore, industrial robots enable safe working in areas that are potentially dangerous for humans. However, industrial robots have disadvantages, such as high acquisition, operating costs, and expertise required for proper setup and programming. Due to high forces and possible injury risks from the end effector, protective devices (e. g., fences) are required. In addition, the advantage of high flexibility includes the disadvantage of low specialization. For example, absolute accuracies are always a disadvantage compared to specialized machine tools.

Due to the high flexibility of the kinematics and the possible end effectors, industrial robots are used in many research projects to improve existing applications and enable novel applications.

One research field using industrial robots is Additive Manufacturing (AM) [7]. Conventional 3D printers are limited in their build space and the three linear axes. With respect to AM, the industrial robot creates more complex components due to its large workspace and degrees of freedom through a controlled material deposition. The dtec.bw research project LaiLa (Labor für intelligente Leichtbauproduktion) investigates automated fiber placement in this context. This research project aims to produce load-path optimized components by automating the process chain. Here, composites are manufactured by depositing unidirectional pre-pregs using Automated Fiber Placement (AFP). By aligning the fibers along complex load paths, the lightweight potential can be exploited more efficiently, which, in addition to cost and resource savings, also contributes to emission reductions in aerospace. To produce components, AM can also be used as a repair process. The dtec.bw research project CORE (Computergesteuerte Bauteilaufarbeitung) deals with robot-guided material deposition by cold spray to repair local damages, considering the example of aerospace components [8]. By using an industrial robot, the guidance of different tools is enabled to repair damages in a specific way.

Other research approaches for using industrial robots deal with the digitalization and networking of the industrial robot. This digitalization can take place as a digital twin (DT) to exchange data between reality and the simulation. In this respect, the DT enables a wide range of applications, such as value chain optimization or predictive maintenance [9–11]. In the dtec.bw research project iMOD (Intelligente modulare Robotik und integrierte Produktionsgestaltung im Flugzeugbau), a DT of a robot is used in the approach to reduce the commissioning time of the robot system [12].

Artificial intelligence (AI) also enables many possible applications for industrial robots to increase autonomy and further optimize processes through AI-based learning [13, 14]. Further digitalization up to Industry 4.0 also offers potential for the application of industrial robots [15]. With complete, intelligent networking, machines such as industrial robots could perform planning in factories and optimize processes adapted to the requirements. The dtec.bw research project EKI (Engineering für die KI-basierte Automation in virtuellen und realen Produktionsumgebungen) deals with the automated foaming of glass panes with polyurethane. To do this, the panes must first be cleaned and pretreated with primer. The primer is an adhesion promoter and must cover the glass wherever PUR is to be foamed later. The robot-guided primer application is monitored by an AI-based visual inspection system and thus enables an increase in product quality.

Overall, the relevance of industrial robots for research and industry is evident from their versatile applications. A future development direction includes cooperation with humans, which is not applicable to industrial robots due to the required protective devices. This collaboration between humans and robots is explored by collaborative robots (Cobots) and presented in the next section.

B. Lightweight Robots

Unlike industrial robots, which are designed to move larger loads, work in isolation from humans, and have minimal physical contact with them, lightweight robots tend to be smaller and designed for lighter loads [16]. They are characterized by high flexibility, as well as the minimum ratio between their weight and maximum payload [17].

Because of these characteristics, they can be used to work collaboratively with humans on the same task and are therefore referred to as collaborative robots, or Cobots. In general, all Cobots are lightweight robots. A lightweight robot, however, is only a Cobot if it is in collaborative service with a human. The first-time collaborative robots were described through a patent by J. Edward Colgate and Michael Peshkin at Northwestern University in 1996. The two authors described a machine that can work in direct physical contact with humans and collaborate with them [18]. However, collaboration should not be confused with cooperation. Although both terms describe an interaction between parties trying to reach a common goal, there is a significant difference: In cooperation, humans and robots work on different subtasks to achieve the common goal, whereas in collaboration, humans, and robots work on the same task together to achieve the goal [19].

Because of the direct contact with humans, they are easy to program compared to industrial robots. For example, the operator can manually guide the robot and thus teach it a certain sequence of movements. In addition, lightweight robots or Cobots are relatively cost-effective and usually do not require as much investment as conventional industrial robots [20].

Especially in today's world and Industry 4.0, where the human factor still plays a major role in the system [21], Cobots are becoming increasingly important. There is a growing demand for more flexibility and mass customization to remain competitive in the market [22]. Collaborative robots precisely address these requirements. The use of Cobots is not intended to displace or substitute humans. Instead, both parties benefit from the joint work, in which the weaknesses of one are the strengths of the other [20].

The control methods are significant when Human-Robot Collaboration (HRC) is used in industrial scenarios. The control methods can be categorized into safety, ergonomics, and efficiency [23]. The safety aspect is of great importance, as the health of the humans collaborating with the robots is of major importance. Therefore, much research is being done in this field to ensure that working with robots is as safe as possible. The ergonomics aspect concentrates on the psycho-physical well-being of the humans collaborating with the robot. The efficiency aims at increasing productivity which is the main goal in industrial applications.

The scientific community favors learning-based control systems, and it is anticipated that they will continue to be researched in the coming future [23]. Therefore, the remainder of this section will be focusing on how learning-based techniques could be used in developing an adequate controller that can be used in HRC for the safety aspect. The safety aspect in HRC is considered to be of great importance followed by efficiency and ergonomics.

For robots to obtain cognitive capabilities to provide a truly safe environment for human interaction, the unpredictable behavior of humans needs to be understood and recognized by the robot [22]. AI, or a subfield called machine learning, can be used to adapt unpredictable patterns of human behavior based on past actions. In this field, researchers see great potential to further develop Cobots. This is supported by the findings of the authors in [24]. They have been able to register an increased growth in works with human-robot collaboration and the use of machine learning.

The authors of [25] have investigated five different machine learning-based approaches for robot-human contact detection. Here, the authors used a dataset of a real robot arm performing asymmetric motions in a collaborative environment. The different approaches classified the data into three types: no contact, intentional, and non-intentional. The authors determined that the ensemble bagging trees approach was superior in classifying the data, with a performance of 97 %. Thus, the authors showed that the developed model could reliably and accurately detect contact between humans and robots to initiate possible countermeasures for human safety.

Through this trend, collaborative work with robots is constantly improving and becoming safer. Contacts with humans can be predicted with increasing reliability and can thus be prevented or intentional contacts, for example through the robot's guidance by the operator, can be differentiated from unintentional ones.

Similarly, several approaches based on machine learning have been used to develop control methods that focus on cognitive ergonomics and physical ergonomics of the human worker as well as increasing the overall efficiency of the industrial applications by minimizing the time needed to complete a task and/or improving the task allocation [23]. Shah [26] claims that HRC can reduce cycle times by about half when compared to using only human workers; it has also been demonstrated that when human workers collaborate with a human-aware robot as opposed to working in human teams alone, idle time can be reduced by 85 %.

Recently, robot manufacturers started to realize the importance of AI in HRC, hence, cognitive capabilities are being implemented within the robot's control systems. For example, Neura Robotics GmbH started producing lightweight robotic arms integrated with AI in its control system which enables safe and intelligent HRC.

With these improvements, Cobots can enter yet unmet fields of application. So far, lightweight robots have mainly found their way into production and medical applications. Here, the robots take over tasks ranging from placing components or product inspections for quality assurance to support in medical procedures. Here, the Cobots help to reach medical equipment or even perform complex surgical procedures [20].

With an expected Compound Annual Growth Rate of 60.85 % and 55.2 % from 2019 to 2024 and 2026, respectively, the full potential of lightweight robots and Cobots today is far from being fully tapped [27, 28]. Through further development, especially in HRC and safety, it is quite conceivable that Cobots will be capable of being used not only in industrial but also in personal environments soon.

In the dtec.bw projects LaiLa and iMOD, lightweight robots are employed. In LaiLa, a lightweight robot is placed on a linear axis to work flexibly on composite parts. This includes tasks such as the automated measuring and sanding of shell structures as well as the application of adhesive to ties. While in iMOD, a lightweight robot placed on rails is used to perform inspection activities on the lower part of the aircraft fuselage.

C. *Mobile Robotic*

One important advantage is missing from the previously described Industrial Robots and Lightweight Robots. They are not mobile and therefore have only a limited range for their end effectors, depending on their current location [1]. Therefore, in recent decades, more and more mobile robots have been successfully deployed in diverse industrial applications, military and security sectors to perform important unmanned missions [29].

Today, mobile robotics is one of the fastest-growing areas of scientific research [30]. They are characterized by the fact that they can move autonomously in their environment and perform tasks independently at their target location without human intervention [30]. In this field, challenges in locomotion, perception, and navigation must be overcome, which form the basis for such a mobile robotic system [31].

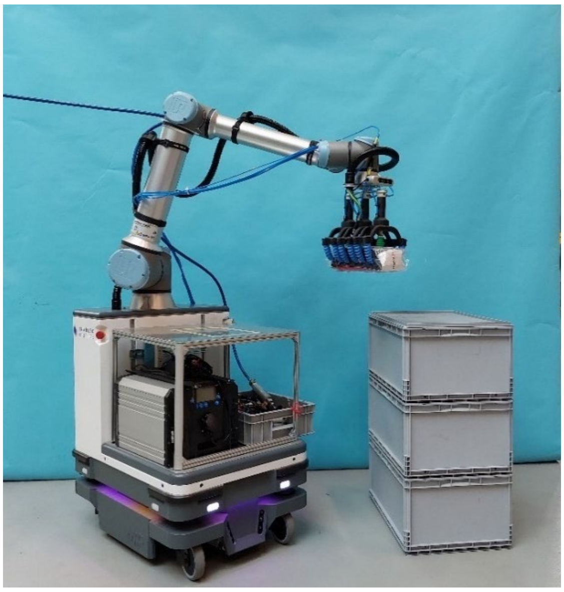


FIGURE 2: MOBILE ROBOT USED IN AULOKOMP.

In the dtec.bw research project iMOD, mobile robots perform various tasks inside and outside the aircraft fuselage. In this context, the transport into the aircraft fuselage, in particular, is a major challenge that needs to be solved [12]. In addition, different use cases are being researched in which mobile robots adhere to the aircraft's outer skin and perform various tasks there, such as inspecting the aircraft's fuselage for any kind of damage.

Robotic manipulation is one of the key challenges in mobile robotics and refers to the interaction of robots with objects. Within this category, pick-and-place is any application where a part is picked up at one location, moved, and placed at another location. Based on the use cases, pick-and-place robots are classified into different categories, and active research is being conducted to improve the existing solutions and develop new alternatives. These categories and some of the recent advances are summarized below.

Robotic Arm: Robotic arms are the most common type of robot for pick-and-place applications. There are various types of end effectors that are attached to the end of a robotic arm to interact with the environment. The authors of [32] provide a list of parameters to help choose an appropriate gripper for industrial applications, while the focus in [33] is only on selection criteria for soft manipulators. Bio-inspired robotic grippers such as the RBO Hand were developed at TU Berlin by [35] and are used for industrial pick-and-place applications at Ocado, the world's largest online grocery retailer.

In 2021, the German supermarket chain REWE invested in its first automated food fulfillment center by adopting the Pick-it-Easy Robotic arm developed by KNAPP, one of the recent fully automatic picking solutions.

Solving the pick-and-place problem in warehouse's picking stations is one of the goals of the dtec.bw project AuLoKomp (Autonomes, flexibles IntraLogistik-Kompaktlager). For this purpose, a softgripper end effector [34] mounted on a mobile robot (see FIGURE 2) is being used, which has the flexibility of the RBO Hand by [35] and can be configured to meet the requirements of picking objects of different shapes. The softgripper was developed at Helmut Schmidt University and has been used in several areas of the food industry.

Delta: The most common configuration of Delta robots has three arms attached to a universal joint and is often used where items need to be picked in groups and placed in assembly patterns. Delta robots have high motion speeds and therefore require fast image processing. Recently [36] combined the use of the modern deep learning approach which works in tandem with the mechanical structure of Delta robots for automatic tea plucking.

Cartesian: Cartesian robots operate in multiple planes. They move in X, Y, and Z axes according to Cartesian coordinates and are widely used for CNC machines and 3D printing. Similar to [36, 37] have equipped a Cartesian robot with a deep-learning-based vision system along with a suction tool end effector. It won the Amazon Robotic Challenge by picking and stowing the most items faster than its competitors.

D. Further Trends

Further trends are concerned with developing simple solutions to shift the focus from an all-encompassing robot to easily expandable robots or to cooperating simple robots. Therefore, modular robotic systems that are part of such considerations are considered below. So are drones, which add an extra dimension to mobile robots and are finding increasing use, especially in teams of robots.

Modular Robotic System: With the increasing desire for customized products, the need for modular workflows is growing. This also affects the use of cost-intensive robots. Conventional robot systems have the disadvantage that the entire application must be re-evaluated and calibrated even for small production adjustments. In contrast, modular robot systems can be adapted to many different tasks, reducing costs.

To ensure adaptation to many different tasks, these systems are modular manipulators with a finite set of modules of different functions. Industrial robots already often have automatic tool changers at the robot's flange. This is the simplest manifestation of a modular manipulator. However, as the variability of the tasks to be handled increases, so does the number of modules.

The modularization of industrial robots is based on the decomposition of their components into their basic functions. The first prototypes of such modular robot systems have existed since the 1980s [38]. As a result of globalization, modular manipulators have become more and more important, so they have evolved over time. The main components of modular manipulators are actuator modules and connection modules, and the end effector module. The actuator modules are responsible for the movement of the robot system and, depending on the requirements, can be pronounced as rotary or pivot joint modules as well as linear modules. The connection modules between the actuators are used to extend the workspace and can also be adapted to any application requirements [39]. In order for the modular robot system to be used for a specific task, a set of robot modules must be found to accomplish that task based on an existing inventory of modules. The criteria for selecting the optimal configuration depend largely on the task requirements. These may include kinematic, dynamic, and obstacle constraints, in addition to performance metrics such as cycle time and energy efficiency [40]. A number of solutions have been developed to solve task-based optimization of robot configuration. These range from using hierarchical elimination in combination with kinematic constraints [40]. On genetic algorithms [41], heuristic search [42] to machine learning [43, 44].

Unmanned Aerial Vehicles: Unmanned aerial vehicles (UAVs) or drones are considered to be a type of autonomous mobile robots that are gaining increasing attention and application, such as in surveillance, transportation, security, and disaster management [45]. The advantage of UAVs over other robots is their ability to fly over terrain or obstacles that are difficult to navigate. In this regard, UAVs can be remotely controlled as well as perform onboard control operations using an autopilot. To do so, they have perceptual capabilities and decision-making autonomy to handle complex tasks without direct human intervention. The demands on these capabilities are increasing, so challenges lie in their cognitive abilities. Another difficulty is limited battery life and, consequently, limited flight time [39]. UAVs differ in various parameters such as configuration, size, range, and weight or even in their equipment such as communication devices, navigation equipment, sensors, and cameras. FIGURE 3 shows an example of a drone with a hexacopter structure that has applications in the dtec.bw research project RIVA (Rechtskonforme IT-Konzepte und -Lösungen für Verbünde autonomer Land-, Wasser- und Luftfahrzeuge). In this project, UAVs are designed to handle various use cases in cooperation with other autonomous mobile robots.

FIGURE 3: UAV USED IN RIVA.

The use of cooperating autonomous mobile robots with different complementary capabilities enables the implementation of complex scenarios such as search & rescue. The robots work together, for example, with UAVs scouting the disaster area and navigating the mobile robots to the appropriate locations. A single robot is not suitable for such a complex scenario. Additionally, tasks can be performed faster, safer, and cheaper than with a highly complex robot that meets all requirements but is not necessarily efficient or robust. Another way to replace expensive and very complex robots is to use modular robotic systems.

III. SUMMARY AND OUTLOOK

In today's world, robots are indispensable machines for handling a wide variety of processes and tasks. This paper presents current trends in robotics that are being used and researched in different dtec.bw projects. Industrial robots offer advantages through high automation and repeatability. The possibility of attaching different end effectors offers the application of different processes, as presented in the example of the project CORE. However, industrial robots do not enable collaborative work with humans due to the high forces involved. Lightweight robots offer the potential to be used in collaboration with humans. This paper described, among other things, their use in the dtec.bw research project LaiLa. Unlike industrial robots, however, they generally cannot handle such large payloads. Mobile robots are characterized by their high degree of flexibility. Their use in the dtec.bw research projects iMOD and AuLoKomp was described in this paper. In particular, the use case of pick-and-place, which is realized by mobile robotics, was addressed. Here, however, there are still challenges in the exact positioning of the robots. Drones used as part of the multimodal approach in the dtec.bw research project RIVA were also presented. The broader topic of modular robotics was also briefly described in this paper.

In the future, more papers will be published that present the research and the use of robots in various research projects in a more intensive way. This article is intended to provide an initial overview. In addition, the concepts and software realization will be discussed in more detail in the future.

ACKNOWLEDGMENT

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project AuLoKomp, iMOD, CORE, LaiLa, EKI & RIVA].

REFERENCES

[1] R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, *Introduction to autonomous mobile robots,* 2nd ed. Cambridge, Massachusetts, London, England: MIT Press, 2011.

[2] J. Mareczek, *Grundlagen der Roboter-Manipulatoren – Band 1*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2020.

[3] *Robotics -- Vocabulary*, ISO 8373:2021(E), International Organization for Standardization, 2021.

[4] W. Weber, *Industrieroboter: Methoden der Steuerung und Regelung,* 2nd ed. München: Hanser Verlag, 2009.

[5] KUKA AG, *KR 1000 titan.* [Online]. Available: https://www.kuka.com/de-de/produkte-leistungen/robotersysteme/industrieroboter/kr-1000-titan (accessed: Aug. 12 2022).

[6] G. C. Devol, JR., "Programmed article transfer," US2988237A.

[7] P. Urhal, A. Weightman, C. Diver, and P. Bartolo, "Robot assisted additive manufacturing: A review," *Robotics and Computer-Integrated Manufacturing*, vol. 59, pp. 335–345, 2019, doi: 10.1016/j.rcim.2019.05.005.

[8] M. Lewke, S. Nielsen, A. List, F. Gartner, T. Klassen, and A. Fay, "Knowledge-based Optimization of Cold Spray for Aircraft Component Repair," in *2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Vasteras, Sweden, 2021, pp. 1–4.

[9] Y. Liu, H. Xu, D. Liu, and L. Wang, "A digital twin-based sim-to-real transfer for deep reinforcement learning-enabled industrial robot grasping," *Robotics and Computer-Integrated Manufacturing*, vol. 78, p. 102365, 2022, doi: 10.1016/j.rcim.2022.102365.

[10] C. Zhang, W. Xu, J. Liu, Z. Liu, Z. Zhou, and D. T. Pham, "Digital twin-enabled reconfigurable modeling for smart manufacturing systems," *International Journal of Computer Integrated Manufacturing*, vol. 34, 7-8, pp. 709–733, 2021, doi: 10.1080/0951192X.2019.1699256.

[11] J. O. Oyekan *et al.,* "The effectiveness of virtual environments in developing collaborative strategies between industrial robots and humans," *Robotics and Computer-Integrated Manufacturing*, vol. 55, pp. 41–54, 2019, doi: 10.1016/j.rcim.2018.07.006.

[12] F. Gehlhoff *et al.,* "Challenges in Automated Commercial Aircraft Production," *IFAC-PapersOnLine*, vol. 55, no. 2, pp. 354–359, 2022, doi: 10.1016/j.ifacol.2022.04.219.

[13] M. Stenmark and J. Malec, "Knowledge-based instruction of manipulation tasks for industrial robotics," *Robotics and Computer-Integrated Manufacturing*, vol. 33, pp. 56–67, 2015, doi: 10.1016/j.rcim.2014.07.004.

[14] R. Pillai, B. Sivathanu, M. Mariani, N. P. Rana, B. Yang, and Y. K. Dwivedi, "Adoption of AI-empowered industrial robots in auto component manufacturing companies," *Production Planning & Control*, pp. 1–17, 2021, doi: 10.1080/09537287.2021.1882689.

[15] K. H. Tantawi, A. Sokolov, and O. Tantawi, "Advances in Industrial Robotics: From Industry 3.0 Automation to Industry 4.0 Collaboration," in *2019 4th Technology Innovation Management and Engineering Science International Conference (TIMES-iCON)*, Bangkok, Thailand, 2019, pp. 1–4.

[16] Y. Cohen, S. Shoval, M. Faccio, and R. Minto, "Deploying cobots in collaborative systems: major considerations and productivity analysis," *International Journal of Production Research*, vol. 60, no. 6, pp. 1815–1831, 2022, doi: 10.1080/00207543.2020.1870758.

[17] S. Popić and B. Miloradovic, "Light Weight Robot Arms-An overview," in *Proceedings of Infoteh*, 2015, pp. 818–822.

[18] James E. Colgate, Michael A. Peshkin, "Cobots," US5952796A, USA, Sep 14, 1999.

[19] A. Weiss, A.-K. Wortmeier, and B. Kubicek, "Cobots in Industry 4.0: A Roadmap for Future Practice Studies on Human–Robot Collaboration," *IEEE Trans. Human-Mach. Syst.*, vol. 51, no. 4, pp. 335–345, 2021, doi: 10.1109/THMS.2021.3092684.

[20] F. Sherwani, M. M. Asad, and B. Ibrahim, "Collaborative Robots and Industrial Revolution 4.0 (IR 4.0)," in *2020 International Conference on Emerging Trends in Smart Technologies (ICETST)*, Karachi, Pakistan, 2020, pp. 1–5.

[21] H. Kinzel, "Industry 4.0 - Where Does This Leave the Human Factor?," *JUCR*, vol. 15, pp. 70–83, 2017, doi: 10.14456/jucr.2017.14.

[22] S. Bragança, E. Costa, I. Castellucci, and P. M. Arezes, "A Brief Overview of the Use of Collaborative Robots in Industry 4.0: Human Role and Safety," in *Occupational and Environmental Safety and Health*: Springer, Cham, 2019, pp. 641–650.

[23] S. Proia, R. Carli, G. Cavone, and M. Dotoli, "Control Techniques for Safe, Ergonomic, and Efficient Human-Robot Collaboration in the Digital Industry: A Survey," *IEEE Trans. Automat. Sci. Eng.*, vol. 19, no. 3, pp. 1798–1819, 2022, doi: 10.1109/TASE.2021.3131011.

[24] F. Semeraro, A. Griffiths, and A. Cangelosi, "Human-robot collaboration and machine learning: a systematic review of recent research," Oct. 2021.

[25] Q. Abu Al-Haija and J. Al-Saraireh, "Asymmetric Identification Model for Human-Robot Contacts via Supervised Learning," *Symmetry*, vol. 14, no. 3, p. 591, 2022, doi: 10.3390/sym14030591.

[26] J. A. Shah, "Fluid Coordination of Human-Robot Teams," *Diss. Massachusetts Institute of Technology*, 2011.

[27] "Global Collaborative Robot Market – Industry Trends and Forecast to 2028," Dec. 2020. Accessed: Aug. 5 2022. [Online]. Available: https:// www.databridgemarketresearch.com/reports/global-collaborative-robot-market

[28] "Global Collaborative Robot (Cobot) Market: Focus on Payload, Application Sales Channel, Component, and Industry - Analysis & Forecast, 2020-2025," Sep. 2020. Accessed: Aug. 5 2022. [Online]. Available: https:// www.researchandmarkets.com/reports/5165436/global-collaborative-robot-cobot-market-focus

[29] B. Tang, Z. Zhu, and J. Luo, "Hybridizing Particle Swarm Optimization and Differential Evolution for the Mobile Robot Global Path Planning," *International Journal of Advanced Robotic Systems*, vol. 13, no. 3, p. 86, 2016, doi: 10.5772/63812.

[30] F. Rubio, F. Valero, and C. Llopis-Albert, "A review of mobile robots: Concepts, methods, theoretical framework, and applications," *International Journal of Advanced Robotic Systems*, vol. 16, no. 2, 172988141983959, 2019, doi: 10.1177/1729881419839596.

[31] M. B. Alatise and G. P. Hancke, "A Review on Challenges of Autonomous Mobile Robot and Sensor Fusion Methods," *IEEE Access*, vol. 8, pp. 39830–39846, 2020, doi: 10.1109/ACCESS.2020.2975643.

[32] G. Fantoni, S. Capiferri, and J. Tilli, "Method for Supporting the Selection of Robot Grippers," *Procedia CIRP*, vol. 21, pp. 330–335, 2014, doi: 10.1016/j.procir.2014.03.152.

[33] J. Hughes, U. Culha, F. Giardina, F. Guenther, A. Rosendo, and F. Iida, "Soft Manipulators and Grippers: A Review," *Front. Robot. AI*, vol. 3, 2016, doi: 10.3389/frobt.2016.00069.

[34] I. Dick, U. Stephan, and B. Rainer, "Analyse und experimentelle Untersuchung eines Handhabungsprozesses in der Pflanzenzucht im Hinblick auf die Anwendbarkeit eines automatisierten Greifsystems," 2021.

[35] R. Deimel and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *The International Journal of Robotics Research*, vol. 35, 1-3, pp. 161–185, 2016, doi: 10.1177/0278364915592961.

[36] H. Yang *et al.,* "Computer vision-based high-quality tea automatic plucking robot using Delta parallel manipulator," *Computers and Electronics in Agriculture*, vol. 181, p. 105946, 2021, doi: 10.1016/j.compag.2020.105946.

[37] D. Morrison *et al.,* "Cartman: The Low-Cost Cartesian Manipulator that Won the Amazon Robotics Challenge," in *ICRA: 2018 IEEE International Conference on Robotics and Automation : 21-25 May 2018, Brisbane, QLD, Australia*, Brisbane, QLD, 2018, pp. 7757–7764.

[38] K. H. Wurst, "The Conception and Construction of a Modular Robot System," *Proc. of 16th Int. Conf. Industrial Robots*, pp. 37–44, 1986.

[39] B. Siciliano and O. Khatib, *Springer Handbook of Robotics*. Cham: Springer International Publishing, 2016.

[40] S. B. Liu and M. Althoff, "Optimizing performance in automation through modular robots," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, 2020.

[41] E. Icer, H. A. Hassan, K. El-Ayat, and M. Althoff, "Evolutionary cost-optimal composition synthesis of modular robots considering a given task," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017.

[42] S. Ha, S. Coros, A. Alspach, J. M. Bern, J. Kim, and K. Yamane, "Computational Design of Robotic Devices From High-Level Motion Specifications," *IEEE Trans. Robot.*, vol. 34, no. 5, pp. 1240–1251, 2018, doi: 10.1109/TRO.2018.2830419.

[43] J. Whitman, R. Bhirangi, M. Travers, and H. Choset, "Modular Robot Design Synthesis with Deep Reinforcement Learning," *AAAI*, vol. 34, no. 06, pp. 10418–10425, 2020, doi: 10.1609/aaai.v34i06.6611.

[44] J. Whitman and H. Choset, "Task-Specific Manipulator Design and Trajectory Synthesis," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 301–308, 2019, doi: 10.1109/LRA.2018.2890206.

[45] S. A. H. Mohsan, M. A. Khan, F. Noor, I. Ullah, and M. H. Alsharif, "Towards the Unmanned Aerial

Vehicles (UAVs): A Comprehensive Review," *Drones*, vol. 6, no. 6, p. 147, 2022, doi: 10.3390/drones6060147.

Drohnengestützte, multivariate Inspektionssysteme zur Zustandserfassung von Stahlbrücken und Stahlwasserbauten

Dominik Thomas*, Max Gündel
Lehrstuhl für Stahlbau und Stahlwasserbau
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Hamburg, Deutschland
*dominik.thomas@hsu-hh.de

Aaron Wickers, Mirco Alpen, Joachim Horn
Professur für Regelungstechnik
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Hamburg, Deutschland

***Kurzfassung* – Bisher erfolgt die Zustandserfassung von Infrastrukturbauwerken alle drei Jahre im Rahmen von Bauwerksprüfungen durch handnahe Untersuchungen. Dies erfordert einen hohen Personal- und Hilfsmitteleinsatz, führt zu Gefahrenstellen und Verkehrsbehinderungen und teilweise subjektiven Ergebnissen. Daher ist es naheliegend, bei der Bauwerksprüfung Drohnen und automatische Auswertealgorithmen zur Unterstützung einzusetzen. Die Herausforderung hierbei ist geeignete kontaktlose Sensorik auszuwählen, um eine ausreichende Detektionswahrscheinlichkeit von Schadensverdachtsfällen zu erreichen. In diesem Beitrag werden erste Ergebnisse der Befliegung von drei Stahlbrücken und einem Wehr vorgestellt, wobei als bildgebende Sensorik hochauflösende RGB-Kameras, Wärmebildkameras und Hyperspektralkameras eingesetzt wurden.**

Stichworte – Bauwerksprüfung, BIM, HSI, Path Planning, UAS

I. EINLEITUNG

Der Bestand an Infrastrukturbauwerken in Deutschland ist mit 52.000 Brücken im Bundesfernstraßennetz, 26.000 Brücken im Netz der Deutschen Bahn und 2.300 Wasserbauwerken der Wasser- und Schifffahrtsverwaltung des Bundes enorm [1], [2], [3]. Diese Infrastrukturbauwerke werden alle drei Jahre abwechselnd einer Hauptprüfung bzw. einer Einfachen Prüfung unterzogen, um sie auf Schäden und Mängel in der Bausubstanz und der Verkehrssicherheit zu überprüfen. Das Ergebnis ist eine Zustandsnote zwischen 1,0 und 4,0, wobei die Note 1 einem sehr guten Bauwerkszustand und die Note 4 einem ungenügenden Zustand mit unmittelbarer Handlungsnotwendigkeit entspricht. Viele Bauwerke sind aufgrund ihres Alters und des stark gestiegenen Anstiegs des Schwerlastverkehrs in einem schlechten Zustand: Aktuell entspricht die Zustandsnote bei 17 % der Bundesfernstraßenbrücken, 35 % der Eisenbahnbrücken und 75 % der Wasserbauwerke der Zustandsnote 3 oder schlechter (ABBILDUNG 1).

Die Bauwerksprüfung wird durch speziell ausgebildete Bauingenieure handnah durchgeführt, wofür unter anderem Brückenuntersichtgeräte, Hubarbeitsbühnen, Pfeilerbefahrgeräte und Zweiwegefahrzeuge zur Unterstützung eingesetzt werden. Dies erfordert eine abschnittsweise Sperrung des Bauwerks mit entsprechenden Verkehrsbehinderungen und Gefahrenstellen, was zu hohen volkswirtschaftlichen Schäden führt.

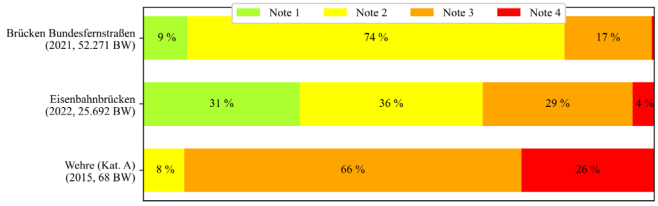


ABBILDUNG 1: GERUNDETE ZUSTANDSNOTEN AUSGEWÄHLTER INFRASTRUKTURBAUWERKE IN DEUTSCHLAND, INKLUSIVE JAHR DER ERHEBUNG UND ANZAHL DER BAUWERKE (BW) [1], [2], [4].

UAS-basierte (unmanned aircraft system) Prüfverfahren bieten das Potential diese Kosten drastisch zu senken, da die Befliegung im laufenden Betrieb durchgeführt werden kann und die Sensorik eine größere Fläche pro Zeiteinheit als ein Bauwerksprüfer untersuchen kann. Zusätzlich wird durch die anschließende Algorithmen-basierte Analyse die Auswertung objektiver und unabhängiger vom einzelnen Prüfer. Im dtec.bw-Projekt MISDRO werden hierzu in Forschungskooperation mit den Unternehmen Boll. Beraten und Planen, Emqopter, Synergeticon und Wölfel Engineering vier Infrastrukturbauwerke aus Stahl der assoziierten Partner Autobahn GmbH, DB Netz AG, Hamburg Port Authority und der Wasserstraßen- und Schifffahrtsverwaltung des Bundes per UAS untersucht.

II. STAND DER FORSCHUNG UND TECHNIK

A. Prüfrichtlinien für Infrastrukturinspektionen

Die Infrastrukturbetreiber prüfen nach unterschiedlichen Richtlinien. Die relevanten Prüfrichtlinien sind in ABBILDUNG 7 dargestellt. Die Gemeinsamkeit der Prüfrichtlinien der unterschiedlichen Verkehrsträger ist der reguläre Inspektionsintervall von drei Jahren sowie die Vergabe einer Zustandsnote von 1,0 bis 4,0.

https://doi.org/10.24405/14559

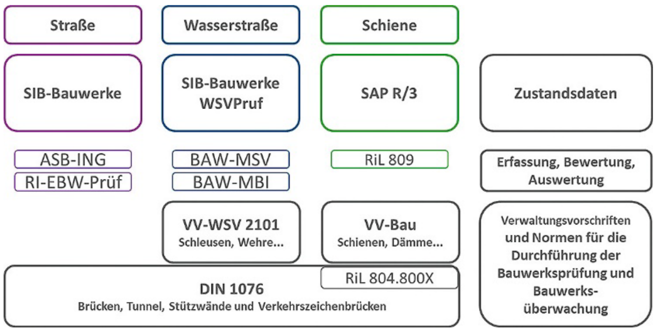


ABBILDUNG 2: ZUSTANDSERFASSUNG VON BAUWERKEN DER DREI VERKEHRSTRÄGER STRAßE, SCHIENE, WASSERSTRAßE NACH [5].

B. *UAS-basierte Bauwerksprüfung*

Die Automatisierung der Bauwerksinspektion per UAS ist aktuell ein sehr aktives Forschungsfeld. Im anglikanischen Raum wurde von Feroz und Dabous 2021 eine Übersicht über „UAV-Based Remote Sensing Applications for Bridge Condition Assessment" veröffentlicht. Insbesondere fehlende Standardisierung, Änderungen der Wetterbedingungen, begrenzte Akkukapazität und rechtliche Rahmenbedingungen schränken hierbei den allgemeinen Einsatz ein. Der Fokus der Forschung liegt auf RGB-Aufnahmen und Analyse von Betonschäden [6].

Im deutschsprachigen Raum wird die UAS-basierte Brückeninspektion u. a. in mehreren Projekten von Blankenbach am Geodätischen Institut der RWTH Aachen verfolgt. Hierzu gehören die Projekte TwinGen, RiverCloud und BIMxD-Bauwerksinspektor XR. An der Bauhaus-Universität Weimar forschte Morgenthal im Projekt „Bewertung alternder Infrastrukturbauwerke mit digitalen Technologien (AISTEC)" um mit hochauflösenden Kameras auf UAS kleine Risse im Beton zu detektieren. Vorgängerprojekte waren von Juni 2013 bis April 2015 „Unbemannte Fluggeräte zur Zustandsermittlung von Bauwerken" und von Januar 2017 bis Juni 2018 die Fortsetzung des Projektes. Im Abschlussbericht zum ersten Projekt konnte die grundlegende Praxistauglichkeit von UAS für Inspektionen zur Unterstützung von Bauwerksprüfern bestätigt werden. Die Datenaufnahme kann per UAS deutlich verkürzt und qualitativ gesteigert werden. Es konnten Risse und Abplatzungen detektiert werden [7]. Im Folgeprojekt wurde hauptsächlich die Datenfusion von RGB- mit Thermographiebildern und die Integration in bestehende BIM-Softwaretools getestet. Hierbei wurde die Größe der Datensätze und Heterogenität der Speicherung festgestellt. Forschungsbedarf wurde insbesondere im Bereich der Datenauswertung und der Datenmodellierung gesehen [8]. 2022 wurde der aktuelle Stand zur Integration der Inspektionsdaten in ein BIM-Modell veröffentlicht [9]. In Österreich lief bis Ende 2019 das Projekt „RISKMON - Anlageninspektion und RISK-MONitoring mit Hochleistungsdrohnen und Sensorik". Wichtige Ergebnisse sind die systematische Analyse zur Einsetzbarkeit von Kameras, Laserscanner, Thermografie, Multispektralanalyse und Georadar für UAS und die Feststellung der besten Einsatzbedingungen. Hierbei wurden auch unter Laborbedingungen Aufnahmen von Beton mit einer Hyperspektralkamera im Wellenlängenbereich von 900 nm bis 1700 nm vorgenommen [10].

Auch die Forschungsinstitutionen der Infrastrukturbetreiber Deutschlands forschen am Einsatz drohnenbasierter Inspektionen [11], [12]. Die DB Fahrwegdienste untersucht im Projekt „Digitale Fernerkundung und Streckenbefliegung mittels unbemannten Luftfahrtsystemen (Drohnen)" (Projekt DigiFE) Drohnenbefliegungen für den Bereich Umwelt- und Naturschutz [13].

Mittlerweile werden UAS-basierte Inspektionssysteme mit RGB-Kameras und Laserscannern auch kommerziell genutzt (u.a. „STRUCINSPECT", „TopSeven" und „Guido Morgenthal Technologien im Bauwesen").

Bisherige Arbeiten und Anwendungen von UAS-basierten Inspektionssystemen konzentrieren sich überwiegend auf Stahlbetonbauten, wobei als Sensorik in der Regel RGB-Kameras aber auch Wärmebildkameras und Laserscanner eingesetzte werden. Allen Projekten gemein ist die Benutzung von RGB-Kameras oder Laserscannern als zentrale Sensorik. UAS-basierte Inspektionssysteme für Stahlbauten wurden bisher nur wenig untersucht.

III. METHODENENTWICKLUNG ZUR DROHNENGESTÜTZTEN ZUSTANDSERFASSUNG VON STAHLBAUTEN

A. *Methodik*

In einem ersten Arbeitsschritt werden Stahlinfrastrukturbauwerke im Hinblick auf typische Schäden und Umgebungsbedingungen für Befliegungen analysiert, um auf dieser Basis Anforderungen an die Sensorik und das UAS zu definieren. Anschließend wird einerseits verschiedene Sensorik zur Detektion der Schäden erforscht und erprobt. Anderseits wird ein Trägersystem mit entsprechender Traglast, Flugeigenschaften und Steuerung entwickelt. Abschließend werden die Sensorik und das Trägersystem zusammengeführt sowie eine gemeinsame Datenplattform zur Analyse und Flugpfadplanung entwickelt.

B. *Automatisierte kontaktlose Zustandsanalyse von Stahlbauten*

Zunächst werden Richtlinien zur Schadensbewertung sowie vorhandene Prüfberichte von Bauwerksinspektionen analysiert, um relevante und typische Schäden an Stahlinfrastrukturbauwerken zu kategorisieren. Relevante Schadenskategorien sind: (i) Verformungen, (ii) Korrosion, (iii) Risse und Rissverdachtsstellen, (iv) Vegetation und Bewuchs, (v) fehlerhafte Entwässerung sowie (vi) fehlerhafte oder fehlende Verbindungsmittel [2], [14] (ABBILDUNG 3, links).

Für diese Schadenskategorien müssen nun geeignete Prüfverfahren ausgewählt oder entwickelt werden. Bei der handnahen Bauwerksinspektion wird hauptsächlich die Sichtprüfung durchgeführt und im Bedarfsfall weitere Prüfverfahren, wie z.B. Ultraschall, hinzugenommen. Bei der drohnengestützten Inspektion müssen hingegen vorwiegend kontaktlose Prüfverfahren eingesetzt werden, wenn ein hoher Flächendurchsatz erwünscht ist. Zusätzlich ist die einsetzbare Sensorik durch die Tragfähigkeit des UAS begrenzt. In einem ersten Schritt sollen HD-RGB-Kameras, Wärmebildkameras, Laserscanner und Hyperspektralkameras erforscht werden und bezüglich ihrer Detektionswahrscheinlichkeit bewertet werden. Für die optische Detektion von Rissen und Rissverdachtsstellen wird zudem die Beleuchtungs- und Aufnahmeart Shape-From-Shading untersucht.

Mit diesen Sensoren werden ein-, zwei und dreidimensionale Aufnahmen erstellt und mit Algorithmen prozessiert. Zudem werden in einem zweiten Schritt die Daten im Sinne eines multivariaten Inspektionssystems fusioniert und gemeinsam ausgewertet, um die Detektionswahrscheinlichkeit zu erhöhen. Abschließend werden Schadensverdachtsstellen auf das BIM-Modell gemappt (ABBILDUNG 3, rechts).

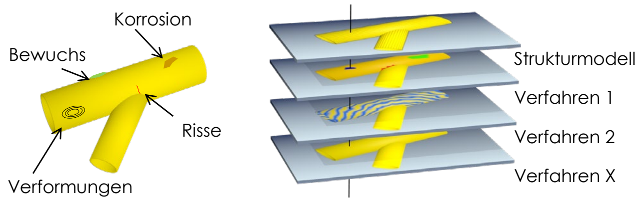


ABBILDUNG 3: SCHEMATISCHE DARSTELLUNG TYPISCHER SCHÄDEN AN STAHLINFRASTRUKTURBAUWERKEN (LINKS), SCHEMATISCHE DARSTELLUNG DER VERWENDUNG MULTIVARIATER AUFNAHME-VERFAHREN AN EINEM BAUTEIL (RECHTS).

C. *Automatisierte Flugplanung und Simulationsumgebung*

Um eine (kontaktlose) Bauwerkprüfung mit Hilfe einer Drohne teilweise oder sogar vollständig zu automatisieren, wird ein hohes Maß an Genauigkeit und Sicherheit gefordert. Zu dessen Gewährleistung wird im Zuge dieses Projekts die erstellte Pfad- und Missionsplanung mit Hilfe der Simulationsumgebung GAZEBO sowie der Kommunikationssoftware ROS2 getestet. Die Inspektionsdrohne sowie auch die zu inspizierenden Bauwerke werden als digitale Modelle eingefügt. Dem Drohnenmodell werden darüber hinaus eine Reihe von Plugins zugewiesen, wodurch eine Steuerung der Drohne möglich wird. Die entsprechenden Steuerbefehle werden in einem eigenen ROS2-Package generiert, welches über die ROS2-Schnittstelle einerseits die Daten der Drohne (Position, Geschwindigkeit, etc.) empfängt und andererseits die Steuerbefehle an die Drohne sendet. Derzeit werden verschiedene Möglichkeiten zum Generieren dieser Steuerbefehle evaluiert. Unter anderem werden ein Modellprädiktiver Ansatz (MPC) sowie ein kaskadierter PID-Regler und ein energiebasierter Regler miteinander verglichen. Eine repräsentative Abbildung von Sensorikelementen ist bislang nur für die Teile geplant, die für die Steuerung und Referenzierung der Drohne notwendig sind. Da zum jetzigen Stand allerdings noch nicht klar ist, welche Sensorik sich am besten eignet, sind hier bisher keine expliziten Angaben zu machen.

Neben der Notwendigkeit eines Reglers, der die Steuerbefehle für gewisse Teilabschnitte, Trajektorien oder Wegpunkte unter Berücksichtigung der aktuellen Zustände der Drohne (Position, Lage, Geschwindigkeit, etc.) generiert, ist es ebenso grundlegend notwendig eine Missionsplanung aufzubauen, die aus einem Bauwerksmodell alle „möglichen und gleichzeitig sinnvollen" Inspektionspunkte extrahieren kann. Hierbei gelten als „möglich" alle Punkte eines Bauwerks, die für die Drohne bzw. den Winkel der Kamera einsehbar sind, ohne dass die Drohne am Inspektionspunkt oder dem Weg dorthin mit einem Hindernis kollidiert. Als darüber hinaus sinnvoll gelten dann alle Punkte, die entweder unbedingt inspiziert werden sollen (manuelle Zuweisung) oder aber in einem bestimmten Abstand zu anderen Inspekionspunkten liegen. Zwar ist eine gewisse Redundanz/Überlappung von Aufnahmen für die Referenzierung der Schäden am Bauwerk durchaus wünschenswert, einen sinnvollen Abstand gilt es jedoch je nach Sensorik noch zu definieren. Schlussendlich werden die extrahierten Punkte durch einen Algorithmus in eine möglichst optimale Reihenfolge gebracht, um eine effiziente Flugkurve und damit mehr Aufnahmen in gleicher Flugzeit zu gewährleisten.

Das Übertragen dieser Konzepte von der Simulationsumgebung in die Realität lässt allerdings vor allem zwei noch zu klärende Fragen offen.

1) Positionsdaten & Georeferenzierung: Bislang erhalten sowohl der Regler als auch die Missionsplanung in der Simulationsumgebung die exakten Daten von Hindernissen und Gebäuden, der Drohne und der anzufliegenden Inspektionspunkte. In der Realität wäre daher eine Verfügbarkeit dieser Daten in Form von GPS-Koordinaten wünschenswert, da ohne eine entsprechende Georeferenzierung keine sinnvolle Zuweisung der Messdaten am Bauwerk möglich ist. Leider ist durch die Verschattung der Bauwerke nicht immer ein vollständiger GPS-Empfang gewährleistet, weshalb es eine Herausforderung sein wird, diese Lücke zu schließen. Hierzu sollen im Rahmen des Projekts einerseits eine höhere Genauigkeit durch RTK-Stationen sowie Verfahren auf Grundlage von Bild- oder Lidar-Daten getestet werden.
2) Sensorik: Für die Steuerung der Drohne und insbesondere für die Kollisions-Vermeidung gilt es weiterhin zu klären, welche Sensorik für den Einsatz an einer Inspektionsdrohne am besten geeignet ist. Es sollen daher verschiedene Optionen (Ultraschall, Lidar, Stereokamera) evaluiert werden, um möglichst genaue Daten zu produzieren. Gleichzeitig gelten aber auch Faktoren wie Gewicht und benötigte Akkukapazitäten als entscheidend, um ein möglichst effizientes Gesamtkonstrukt zu gewährleisten.

IV. ERSTE ERPROBUNG DER DROHNENGESTÜTZTEN ZUSTANDSERFASSUNG IN REALLABOREN

A. *Referenzbauwerke*

Für die Erforschung und Erprobung der automatisierten Bauwerksinspektionssysteme wurden von den assoziierten Partnern vier Stahlinfrastrukturbauwerke als Reallabore zur Verfügung gestellt: (i) Norderelbbrücke der A1, Schrägkabelbrücke, Baujahr 1963; (ii) Bahnbrücke über die Oste der Bahnstrecke Hamburg-Cuxhaven, Fachwerkbrücke, Baujahr 1943; (iii) Freihafenelbbrücke über die Norderelbe, Fachwerkbrücke, Baujahr 1926, und (iv) Weserwehr Dörverden, Baujahr 1934. Für alle Bauwerke sind Instandsetzungs-/Neubaumaßnahmen vorgesehen. Zusätzlich wird die stillgelegte Travehafenbrücke im Hamburger Hafen zur Erprobung der Drohnen und der Sensorik verwendet.

B. *Erstbefliegungen*

In einem ersten Schritt wurden die Referenzbauwerke mit marktüblichen Drohnen beflogen und mit RGB- und Wärmebildkameras fotografiert. Ferner wurden manuell Aufnahmen per Kompakt-, Spiegelreflex- und Hyperspektralkameras vorgenommen. Aus den Aufnahmen der UAS-montierten und händisch getragenen RGB-Kameras können bei ausreichender Überlappung photogrammetrisch Farbpunktwolken berechnet werden, welche als erstes digitales Bauwerksmodell dienen. In ABBILDUNG 4 ist beispielhaft eine aus RGB-Bildern berechnete Punktwolke der Bahnbrücke über die Oste dargestellt, die als erstes digitales Bauwerksmodell dient. Eine höhere Genauigkeit kann durch den Einsatz aktiver Laserscanverfahren erreicht werden. Dies wurde drohnenbasiert an der Travehafenbrücke getestet. Der Abstand zur Brücke betrug durchgängig ca. 20 m. Die erwartete vertikale Genauigkeit liegt bei 5 cm und die horizontale Genauigkeit bei 10 cm. Für die Detektion von Beulen und Verformungen ist dies noch unzureichend. Die berechnete Punktwolke in ABBILDUNG 5 enthält inklusive Umgebung 61.735.000 Punkte. Die Verschattungen im Bereich der Bauteilverbindungen und fehlende Passpunkte an der Wasseroberfläche führen für photogrammetrisch und LIDAR-berechnete Punktwolken zu unzureichenden Ergebnissen. Die Verschattungen können jedoch durch Bauteilnahe Befliegungen verringert werden.

ABBILDUNG 4: AUF BASIS VON RGB-BILDERN PHOTOGRAMMETRISCH ERSTELLTE FARBPUNKTWOLKE DER BAHNBRÜCKE ÜBER DIE OSTE.

ABBILDUNG 5: AUF BASIS VON LIDAR-DATEN ERSTELLTE FARBPUNKTEWOLKE DER TRAVEHAFENBRÜCKE IM HAMBURGER HAFEN.

Die Aufnahmen aus den Erstbefliegungen wurden zudem für erste Versuche zur Schadensdetektion verwendet. In ABBILDUNG 6 links ist beispielsweise auf einer RGB-Aufnahme Korrosion am Anschluss eines Horizontalverbandes zu erkennen. Mit einer Wärmebildkamera werden bei einer Auflösung von 640x512 Pixel und einer Genauigkeit von ± 2 °C die Kältebrücke der ordnungsgemäßen Befestigung des Wehrfeldes sichtbar (ABBILDUNG 6, rechts).

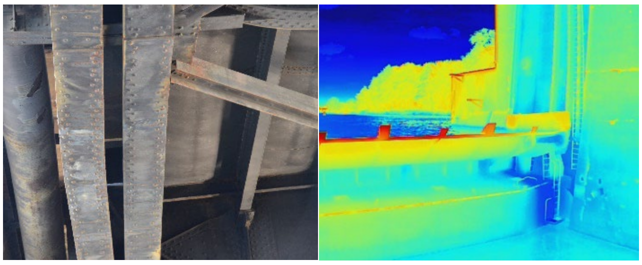


ABBILDUNG 6: UNTERSICHTAUFNAHME DER FREIHAFENELBBRÜCKE MIT EINER SPIEGELREFLEXKAMERA (LINKS), WÄRMEBILD DES WEHRFELDES UND -PFEILERS DES WESERWEHR DÖRVERDEN UNTER DIREKTER SONNENEINSTRAHLUNG (RECHTS).

Eine Alternative zur RGB-Kamera ist die Hyperspektralkamera. Bei einer RGB-Kamera hat jeder Pixel die 3 Farbinformationen rot, grün und blau. Bei einer Hyperspektralkamera enthält hingegen jeder Pixel die Informationen eines nahezu kontinuierlichen Spektrums.

ABBILDUNG 7: PER HNDVI-INDEX UND FALSCHFARBENDARSTELLUNG HERVORGEHOBENE VEGETATION AN DER NORDERELBBRÜCKE AUS EINER HYPERSPEKTRALAUFNAHME.

Zur Erprobung wurde eine Hyperspektralkamera mit einer Auflösung von 1000x1000 px und 125 Bändern über die Wellenlänge 450 nm bis 950 nm eingesetzt. Für die Falschfarbendarstellung der Vegetation wurde der (hyperspectral) Normalized Difference Vegetation Index eingesetzt (ABBILDUNG 7). Die hier verwendete Definition ist

$$hNDVI = \frac{NIR - Rot}{NIR + Rot} \quad (1)$$

mit dem NIR-Signal bei 827 nm und dem Rot-Signal bei 668 nm [15]. Über weitere spektrale Indizes können andere Materialien hervorgehoben werden, z.B. Wasser über den Normalized Difference Vegetation Index [16].

V. AUSBLICK

Nach der Erstellung des Lastenheftes für das Inspektionssystems und den ersten Datenaufnahmen wird in den nächsten Schritten die Sensorik getestet und deterministische und Machine Learning-Algorithmen zur Flugplanung und Zustandsanalyse erforscht.

Des Weiteren ist die Erstellung eines Bilddatensatzes typischer Stahlbauschäden mit visuellen und Hyperspektralaufnahmen vorgesehen um ML-Modelle trainieren und validieren zu können. Mithilfe des Datensatzes werden weitere spektrale Indizes getestet, wie der Normalized Difference Water Index, aber auch die optimalen spektralen Bänder zur Detektion von Korrosion bestimmt. Eine Herausforderung sind die Lichtverhältnisse am Bauwerk und zwischen Bauwerk und UAS, da sie sich bereits während einer Befliegung (direkte Sonneneinstrahlung und diffuses Licht durch Bewölkung) ändern können. Für die Kameras ist der dafür erneut notwendige Weißabgleich problematisch, da an der Drohne andere Belichtungsverhältnisse vorliegen als an einem zu fotografierenden Bauteil.

Die Aufnahmen und detektierte Schäden werden auf BIM-Modelle der Bauwerke projiziert, die wiederum für die Bauteilabhängige-Segmentierung der Punktwolken und zur Bestimmung von Geometrieabweichungen zum as-planned BIM-Modell, sowie zwischen zwei Inspektionen eingesetzt werden.

Mithilfe der 3D-Modelle können zusätzlich unterschiedliche Beleuchtungssituationen und Schadensfälle simuliert werden.

Die detektierten Schäden werden final in einer zentralen Datenbank gespeichert und mit einer Weboberfläche, inklusive 3D-Anzeige, visualisiert, sodass Bauwerksverantwortliche den aktuellen Zustand unmittelbar sehen können und eine schnelle Beurteilung und Veranlassung weiterer Maßnahmen möglich ist.

DANKSAGUNG

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt MISDRO]. Ferner gilt ein besonderer Dank Oberstleutnant Kubik und HSU-Studierenden für die logistische Unterstützung der Brückenbefahrungen mit einem Schlauchboot der Bundeswehrpioniere. Zusätzlich bedanken wir uns bei Florian Steffens für die Vorführung und Austausch des bei der HPA eingesetztem UAS.

LITERATUR

[1] BASt, „Zustandsnoten der Brücken (Excel),“ 09 2021. [Online]. Available: https://www.bast.de/DE/Statistik/Bruecken/Zustandsnoten-excel.xlsx. [Zugriff am 01 09 2022].

[2] BAW, „Schadensklassifizierung an Verkehrswasserbauwerken (MSV),“ Bundesanstalt für Wasserbau, Karlsruhe, 2018.

[3] Deutsche Bahn, „DB Infografik: Bahnbrücken in Deutschland,“ 05 2019. [Online]. Available: https://www.deutschebahn.com/resource/blob/259996/80a8cf76e5758231ef7dfa4d5fc1380e/infografik_bruecken_bauform_alter-data.pdf. [Zugriff am 01 09 2022].

[4] DB Netz AG, „Deutschlands Eisenbahnbrücken | DB Netze Brückenportal,“ [Online]. Available: https://bruecken.deutschebahn.com/. [Zugriff am 2022 09 01].

[5] I. Hindersmann und S. Staub, Herausforderungen für ein Lebenszyklusmanagement für Bauwerke der Verkehrsinfrastruktur – Ergebnisse von leitfadengeführten Experteninterviews, Bautechnik, 2022.

[6] F. Ioli, Pinto, Alessandro und L. Pinto, „UAV PHOTOGRAMMETRY FOR METRIC EVALUATION OF CONCRETE BRIDGECRACKS,“ *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* pp. 1025-1032, 2022.

[7] G. Morgenthal, N. Hallermann und M. Achtelik, Unbemannte Fluggeräte zur Zustandsermittlung von Bauwerken. Abschlussbericht, Stuttgart (Deutschland): Fraunhofer IRB Verlag, 2015.

[8] N. Hallermann, P. Debus, J. Taraben, A. Benz, G. Morgenthal, V. Rodehorst, C. Völker, T. Abbas, T. Gebhardt und S. Daubert, Unbemannte Fluggeräte zur Zustandsermittlung von Bauwerken - Fortsetzungsantrag, Stuttgart: Fraunhofer IRB Verlag, 2019.

[9] J. Taraben, M. Helmrich und G. Morgenthal, Datenmodelle für digitale Zwillinge von Brücken und bildbasierte Zustandsaufnahmen, Bd. 99, Bautechnik, 2022.

[10] M. Hoffmann, T. Dolleschal und A. Strauss, „RISKMON - Anlageninspektion und RISK-MONitoring mit Hochleistungsdrohnen (UAS/UAV),“ Wien, 2019.

[11] J. Blankenbach und R. Becker, „Rivercloud,“ 2020. [Online]. Available: http://www.rivercloud.org/.

[12] G. Morgenthal, V. Rodehorst, N. Hallermann, P. Debus und C. Benz, „Bauwerksprüfung gemäß DIN 1076 – Unterstützung durch (halb-)automatisierte Bildauswertung durch UAV (Unmanned Aerial Vehicles – Unbemannte Fluggeräte),“ 2021.

[13] DB Fahrwegdienste GmbH, „DB Fahrwegdienste GmbH,“ DB Fahrwegdienste GmbH, [Online]. Available: https://fahrweg.dbnetze.com/fahrweg-de/unternehmen/db_netz_ag/externe_organisationen/fahrwegdienste-1368662. [Zugriff am 24 08 2022].

[14] BMVI, Richtlinie zur einheitlichen Erfassung, Bewertung, Aufzeichnung und Auswertung, von Ergebnissen der Bauwerksprüfungen nach DIN 1076, Berlin: Bundesministerium für Verkehr und digitale Infrastruktur, 2017.

[15] A. Jung, P. Kardevan und L. Tökei, „Hyperspectral Technology in Vegetation Analysis,“ Progress in Agricultural Engineering Sciences, 2006.

[16] B.-c. Gao, „NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space,“ *Remote Sensing of Environment,* Bd. 3, Nr. 58, pp. 257-266, 1996.

[17] A. Taffe, M. Krämer, M. Schiemann und J. Wiese, „ZfPBau-Verfahren für Ingenieurbauwerke aus Stahl und Umsetzung einer Logik für die Nutzung un den Abruf der Daten,“ Deutsches Zentrum für Schienenverkehrsforschung beim Eisenbahn-Bundesamt, Dresden, 2021.

[18] A. Nuber, „MISO-Inspector – Multivariates Inspektionssystem - Abschlussbericht,“ Höchberg, 2022.

[19] U. Kiehne, „Zustand der Wasserbauwerke in der WSV,“ Bundesanstalt für Wasserbau, 27 10 2015. [Online]. Available: https://izw.baw.de/publikationen/kolloquien/0/02_Kiehne_Zustand-Wasserbauwerke-WSV.pdf. [Zugriff am 01 09 2022].

Generic Model Structure for the Representation of Flexible Energy Resources and Their Joint Optimization

Lukas Peter Wagner*, Lasse Matthias Reinpold, Lena Scholz, Vincent Henkel, Maximilian Kilthau, and Alexander Fay
Helmut-Schmidt University, Institute of Automation Technology
Hamburg, Germany
{*lukas.wagner, lasse.reinpold, scholzl, vincent.henkel, maximilian.kilthau, alexander.fay}@hsu-hh.de

Nicolas Neubauer and Carsten Schütte
Hamburg University of Applied Sciences, Competence Center for Renewable Energies and Energy Efficiency
Hamburg, Germany
{nicolas.neubauer, carsten.schuette}@haw-hamburg.de

Nils Loose and Christian Derksen
University of Duisburg-Essen, SOFTEC
Essen, Germany
{nils.loose, christian.derksen}@uni-due.de

Abstract **– Modeling energy resources is essential to benefit from their inherent energy flexibility. This paper describes a generic model structure to model flexible energy resources. Based on the presented generic model structure, an electrolyzer connected with a hydrogen storage system is modeled and its operation is subsequently optimized to minimize operational expenses. Within the case study the participation of the modeled system in the intra-day market for electric energy is analyzed. The results of the analysis illustrate the potential of energy flexibility by optimally responding to external signals, e.g., prices for electric energy.**

Keywords – Energy flexibility, Generic Model, Energy resource, Optimization

NOMENCLATURE

c_{el} in EUR/MWh	Cost of electric energy
$C_{Storage}$ in kWh	Capacity of the energy storage
EUR	Euro
H in kWh	Hydrogen production target
h_i in kW	Hydrogen power output in i
i	Index for time interval
$\eta(x)$	Efficiency in dependence on x
P in kW	Power
SOC	State of charge
$t, \Delta t$	Time, Time interval
Ω	Generic factor

I. INTRODUCTION

According to the Paris Agreement, many countries aim to achieve a carbon neutral economy by 2050. This implies that, among other things, the renewable energy generation capacity needs to be massively expanded within the coming decades [1]. Major renewable energy resources like wind and solar power entail the challenge of intermittent availability.

This has an impact on both spot market electricity pricing and power grid stability. A possible approach to tackle these challenges is to leverage the flexibility of individual components of the power system's components [2]. This can be accomplished using storage systems like batteries and material buffers or by shifting the electricity demand towards times when renewable energy is abundant.

Flexibility is defined as a capability of a system able to execute different paths of action at given occasions. Systems providing energy flexibility are able to temporally decouple energy demand from its supply [3]. This ability can be classified into demand-side and supply-side flexibility, as well as the flexibility of energy storage systems. This study considers the latter as it has the greatest flexibility potential. Zhao *et al.* show that making use of energy flexibility can result in lower operational expenses [4]. For minimizing the costs, mathematical modeling of energy resources with a subsequent optimization of their operation is commonly applied. To simplify this engineering process and to provide consistent models, a generic model structure to represent flexible energy resources is presented here.

Several previous publications deal with the topic of generic mathematical model structures which are used to optimize the operation of flexible energy resources. A review for the modeling approaches and the optimization of integration of renewable energy resources is provided by Wagh and Kulkarni [5]. Schott *et al.* present a descriptive data model for industrial flexibility with respect to power consumption which was developed in the *Kopernikus* project *SynErgie* [6]. Khatri *et al.* develop a generic modeling approach which is used to consider the active participation of industrial enterprises in electricity markets [7]. Whereas Corsetti *et al.* deal with the modeling and deployment of multi-energy flexibility as an energy lattice framework [8].

Energy hubs provide the possibility to model complex energy systems with multiple conversions and multiple

https://doi.org/10.24405/14560

energy flows [9]. This concept serves as a foundation for a generic framework for the modeling of energy systems that include numerous energy carriers presented by Krause *et al.* [10]. It can also be applied in combination with the power nodes modeling framework which focusses on modeling energy storage systems [11]. Both concepts enable the user to conduct detailed, system level investigations. To model one energy resource without multiple energy carriers, the authors formulate the hypothesis that a simplified approach can be used. The detailed analysis of current research in energy resource modeling results in the awareness that a generic model structure is needed which is described in this paper. Therefore, the main contribution of this paper is a generic model structure for energy resources with an appropriate level of detail for the optimization and its application to a use case.

The generic model structure is intended to represent a wide variety of flexible energy resources from energy converters like electrolyzers or diesel engines over storage systems like batteries or material buffers to production machines and processes or household appliances. The mathematical representations of these energy resources allow their use in optimization models which can determine the most economic or the most climate-friendly operation schedule.

To demonstrate the applicability of the presented model structure, it is applied to model a hydrogen production facility consisting of an electrolyzer and a hydrogen storage system. To illustrate the benefit of flexible energy resources, a comparison of static operation with a fixed operation point and variable operation, optimizing the participation at the intra-day market is carried out.

This paper is structured as follows: Sec. II describes the methodology applied in modeling and optimization. The case study in Sec. III analyzes the energy flexibility inherent to the hydrogen production facility. A critical reflection and conclusion is given in Sec. IV.

II. GENERIC MODEL FOR FLEXIBLE ENERGY RESOURCES

Based on the state of the art outlined in Sec. I, this section presents the methodology applied to build models for energy flexibility. First a generic model structure is presented (Sec. II -A). The methodology for the optimization is presented in Sec. II -B.

A. *Generic Model for Energy Flexibility*

The analysis of different mathematical models shows that a lot of different models representing energy resources exist. However, to ensure that every model of different energy resources provides the same structure, a generic model structure is built and presented in the following.

TABLE 1: SELECTED MATHEMATICAL MODEL OF FLEXIBLE ENERGY RESOURCES.

Energy Resource	***Relevant Equations***
Electrolyzer [12–18]	$P(t)_{out} = P(t)_{in} \cdot \eta(P_{in}(t))$ $\mathrm{P}(t)_{in} \leq \mathrm{P_{max}}$
BESS [19–21]	$\mathrm{SOC}(t+\Delta t) = \mathrm{SOC}(t) + \frac{P_{charge} \cdot \eta_{charge} \cdot \Delta t}{C} - \frac{P_{dis} \cdot \Delta t}{C \cdot \eta_{dis}}$ $SOC_{min} \leq SOC(t) \leq SOC_{max}$
Wind Turbine [22–24]	$\mathrm{P}(\omega(t)) = \begin{cases} P^u_{rated} & \omega_{min} \leq \omega(t) \leq \omega_u \\ x(\omega(t)) \cdot P_{rated} & \omega_u \leq \omega(t) \leq \omega_{max} \\ 0 & \omega(t) \leq \omega_{min} \; or \; \omega_{max} \geq \omega(t) \end{cases}$ x is a factor representing throtteling at higher windspeeds.
Solar PV [25–27]	$P_{out}(t) = P_{installed} \cdot \eta \cdot x(t)$ x is a factor representing solar irradiation

The equations listed in TABLE 1 determine the power output of the respective system. For energy resources generating electrical energy of renewable resources, the calculation is conducted by multiplying the maximum or rated power by an operation point or other influencing factors such as wind speed. In addition, energy resources which convert one energy carrier into another and are controllable are modeled somehow different. An electrolyzer, for example, converts electric energy into chemically bonded energy in the form of hydrogen. The conversion depends on the power input and always causes power losses. As stated in Eq. 1, it is possible to model this energy resource and its dependencies. An energy resource's power output P_{out} can be calculated from its power input P_{in} and – if applicable – the corresponding efficiency $\eta(P_{in})$. η also represents influencing factors in case of renewable generation. To represent the energy resource as accurately as possible, a minimum $P_{in,min}$ and maximum input power $P_{in,max}$ can also be set as model constraints.

$$P_{out}(P_{in}) = \begin{cases} P_{in} \cdot \eta(P_{in}), & P_{in,min} \leq P_{in} \leq P_{in,max} \\ 0, & P_{in} < P_{in,min} \end{cases} \quad (1)$$

This generic model structure can be extended to represent the dynamic behavior of energy resources such as the response to a change in the operating set point or a change of its environment, i.e., its boundary conditions. Further limitations can be imposed on the permissive operating conditions, e.g., regarding operating hours or dependencies to other systems.

The generic model description shown in Eq. 1 is also applicable to energy storage systems. The power input P_{in} can be coupled to the power output of another system, as shown in Eq. 2. The state of charge (SOC) of the storage is calculated by an energy balance (Eq. 3). The SOC of a given time step $(t_i + \Delta t)$ depends on the SOC of the previous time step (t_i) as well as the power input P_{in} and output P_{out} of the storage during the time step Δt divided by the storage's capacity $C_{Storage}$ and the efficiency of (dis-) charging $\eta(P_i)$. Further, the energy generation target per interval and desired power output can be defined according to the system configuration and the modeler's needs.

$$P_{in,Sys2} = P_{out,Sys1} \quad (2)$$

$$\mathrm{SOC}(t_i + \Delta t) = \mathrm{SOC}(t_i) + \frac{|P_{in}| \cdot \eta_{in}(P_{in}) \cdot \Delta t}{C_{Storage}} - \frac{|P_{out}| \cdot \Delta t}{C_{Storage} \cdot \eta_{out}(P_{out})} \quad (3)$$

The time resolution of the model can be adapted to fit the needs of the researcher. Guidelines for a suitable time-resolution of a model of flexible energy resources are provided by Cao and Sirén [28]. Often an interval of 15 minutes is selected if an analysis aims at intraday power market participation.

To instantiate the generic model, data about the energy resource's system characteristics, the maximum or rated power, and possible limits of the operational point need to be known. In addition, the capacity and efficiencies (if applicable) of the storage is also needed.

B. Optimization

To optimize the use of the energy flexibility described by the instantiated generic model, an optimization problem must be formulated. To implement unified models of energy resources, the optimization problem is based on the presented generic model approach. In addition, an objective function and operational constraints must be established.

The optimization problem can realize the maximization or minimization of the objective function according to Eq. (*4*) depending on the power, as well as possible generic factors Ω_i, which represent for example the current energy prices.

$$\text{min/max}\, objective = \sum_{i=0}^{t_{max}} P_i \cdot \Delta t \cdot \Omega_i \tag{4}$$

On the basis of this objective function, which satisfies the criteria of a linear optimization problem according to , Unger and Dempe [29], the function can be optimized in dependency on the decision variable (Eq. 4: P_i).

Furthermore, constraints need to be set and considered, which can be deduced from the mathematical description of the generic model. For example, constraining the power input of the system so that the power neither falls below a defined minimum value nor exceeds a defined maximum value (see Eq. 5). This constraint can be derived from Eq. 1. Additional constraints might be set for, e.g., energy production within the interval.

$$P_{in,min} \leq P_{in} \leq P_{in,max} \tag{5}$$

If multiple systems are coupled together, it is also necessary to ensure that the input power of system 2 is equal to the output power of system 1 (see Eq. 2).

III. Case Study

Within this case study, the generic model is instantiated for an electrolyzer and a hydrogen storage system. After demonstrating the applicability of the approach, the model is used to optimize the electric energy to hydrogen conversion against a historic prices for electric energy traded in the intra-day market provided by EPEX SPOT [30].

As an exemplary energy resource, the electrolyzer Siemens *Silyzer 200* with a rated electric power of 6,000 kW is modeled using the characteristics derived from real operation. As a modeling environment, the *Energy Option Model* [31] is used in combination with the solver IBM CPLEX [32].

Eqs. 7-9 describe the electrolyzer and its storage system by instantiating the generic model developed in Sec. II. The objective function (Eq. (*6*)) describes the minimization of the costs of electric energy through power consumption.

$$\text{min}\, objective = \sum_{i=0}^{t_{max}} P_{el,i} \cdot \Delta t \cdot c_{el,i} \tag{6}$$

Eq. 7 instantiates the generic model described in Sec. III using the characteristics of the electrolyzer.

$$\mathrm{P}_{hydrogen} = P_{el} \cdot \eta(P_{el}) \tag{7}$$

Equations 8-11 represent constraints for the operation: Eq. 8 limits the electric power (see Table 2), Eq. 9 represents the storage and constrains the operation to not overfill the storage.

$$P_{el,\,min} \leq P_{el} \leq P_{el,\,max} \tag{8}$$

$$0 \leq SOC(t_i) \leq 1 \quad \forall t \tag{9}$$

Apart from Eq.3, which is applied as a constraint to represent the energy balance in the hydrogen storage system, Eqs. 10 & 11further define the operation by setting targets for the hydrogen production in the interval H and the power output of the storage (or of the electrolyzer directly) h_i. h_i can also be interpreted as the hydrogen demand of a consumer.

$$\sum_{i=0}^{t_{max}} P_{Hydrogen,\,i} \cdot \Delta t = \mathrm{H} \tag{10}$$

$$P_{out,Storage,\,i} = h_i \tag{11}$$

Two operation modes of the electrolyzer are compared: Inflexible operation with a fixed operation point and flexible operation with the ability of the process to modulate its power input between $P_{el,min}$ and $P_{el,max}$. Due to its operation mode, no hydrogen storage system is necessary to operate the energy resource in the inflexible mode. In both cases the constraints described in Eqs. 10 & 11 are satisfied and the total amount of hydrogen produced is the same. The selected time interval for the case study is August 12th until August 21st, 2022. Values for all key parameters are shown in Table 2.

Table 2: Key Parameters and Results of the Comparison.

Parameter	*Flexible*	*Inflexible*
Cost of electric energy	398,207 EUR	430,140 EUR
Hydrogen production H	599 MWh	599 MWh
Hydrogen demand h_i	2,500 kW	2,500 kW
Hydrogen output electrolyzer	900 … 3,700 kW	2,500 kW
Storage size $C_{Storage}$	10,000 kWh	0 kWh
Electric power P_{el} of electrolyzer	1,200 … 6,000 kW	4,000 kW

The analysis shows that reacting to prices of electric energy at the intra-day market yields 7 % lower costs compared to the inflexible operation. The grey curve in Figure 1 shows the difference between the hydrogen output of the hydrogen production system between the flexible and the inflexible operation modes over an exemplary timespan of 30 hours. To achieve the previously stated savings, the hydrogen output power of the electrolyzer alternates between the maximum and minimum permissible operating point, deviating from the average hydrogen demand h_i by more than ± 1 MW as shown in Figure 1.

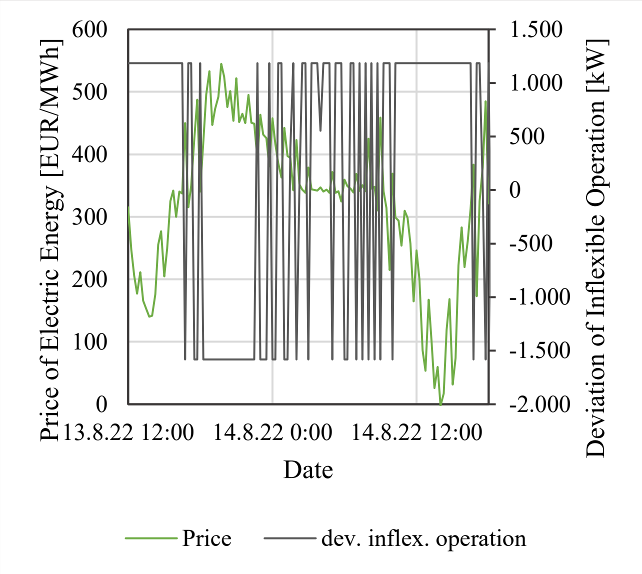


FIGURE 1: PRICE OF ELECTRIC ENERGY (GREEN) [30] AND DEVIATION OF THE FLEXIBLE OPERATION FROM INFLEXIBLE OPERATION (HYDROGEN OUTPUT, GREY).

FIGURE 2 shows the corresponding state of charge in the same representative time interval. The grey curve in FIGURE 2 demonstrates that the hydrogen storage system is charged during the hours exhibiting the lowest electricity prices. Correspondingly, the hydrogen storage system is discharged during the hours exhibiting the highest electricity prices.

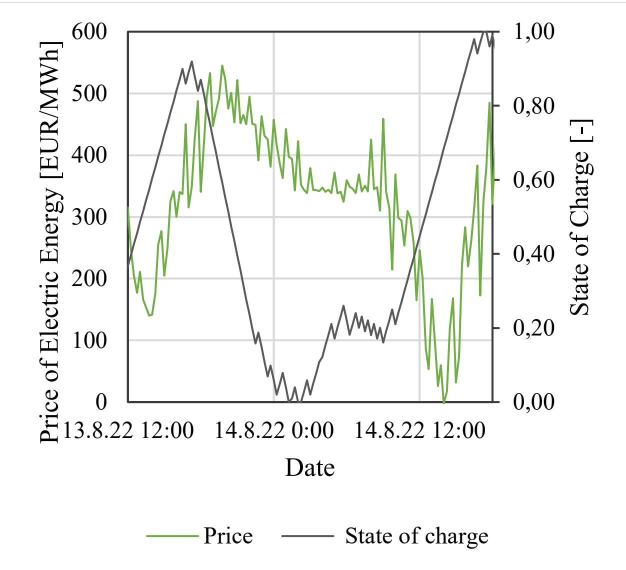


FIGURE 2: PRICE OF ELECTRIC ENERGY (GREEN) [30] AND SOC (FLEXIBLE OPERATION, GREY).

The analysis shows that a flexible operation of the electrolyzer is favorable compared to a static operation with a fixed operation point in terms of cost savings achieved through real-time pricing.

IV. DISCUSSION AND CONCLUSION

This paper presents a generic model structure to represent flexible energy resources and to optimize their operation. The model structure is derived from multiple energy resource models of different energy resources found in other publications. The applicability is demonstrated in a case study where the generic model is instantiated to model an electrolyzer and a hydrogen storage system. Subsequent optimization based on the model, including respective constraints, shows financial benefits of energy flexibility compared to inflexible operation.

While the applicability of the generic model structure is demonstrated in this case study, several assumptions are made that might not be applicable to other case studies. To simplify the case study, it was assumed that the production capacity of the electrolyzer and the storage capacity of the hydrogen storage system are fixed values. Future case studies can extend this optimization to include the capacities of the two energy resources as optimization variables to solve the resulting component sizing problem. This entails the need to include other important cost factors such as the capital expenditure of both systems in the optimization problem or other operational expenses, such as costs for rapidly changing the operational point which can lead to increased degradation of the electrolyzer, even though it has been shown in [33] that this impact is negligible. Moreover, successive projects should aim to more precisely reflect the real technical behavior of implemented units, e.g., by implementing ramping constraints. To include additional factors of the energy price course such as lower PV production in winter, a longer timespan than the 10 days considered in this study is desirable.

Another challenge to be addressed in future works are the uncertainties regarding the energy prices on the EPEX SPOT markets which need to be considered in forecasted flexibility scheduling. Today, prices for intraday energy trading are only available for a certain day from 3 pm on the previous day and even these prices are subject to changes up until five minutes before power delivery is due. This means that an optimization of the operation schedule beyond the next day is subject to major uncertainties. While methods exist to predict prices for different power markets, future works should consider the statistical uncertainty in price predictions and implement it in the modeling approach. An existing approach to address this uncertainty is statistical programming, which will be implemented on top of the existing methods in future works.

ACKNOLODGEMENT

This paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project OptiFlex]. This work was also supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) (PTJ, FKZ: 03EI6035A), by the Federal Ministry Education and Research (BMBF) (PTJ, FKZ: 03HY116), as well as by the project "Northern German Living-Lab" (NRL, 03EWR007T2).

REFERENCES

[1] European Commission, *Going climate-neutral by 2050: A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*. Luxembourg: Publications Office of the European Union, 2019.

[2] Emil Hillberg *et al.*, "Flexibility needs in the future power system," 2019.

[3] N. Lehmann, E. Kraft, C. Duepmeier, I. Mauser, K. Förderer, and D. Sauer, "Definition von Flexibilität in einem zellulär geprägten Energiesystem," 2019.

[4] J. Zhao, T. Zheng, and E. Litvinov, "A Unified Framework for Defining and Measuring Flexibility in Power System," *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 339–347, 2016, doi: 10.1109/TPWRS.2015.2390038.

[5] M. M. Wagh and V. V. Kulkarni, “Modeling and Optimization of Integration of Renewable Energy Resources (RER) for Minimum Energy Cost, Minimum CO2 Emissions and Sustainable Development, in Recent Years: A Review,” *Materials Today: Proceedings*, vol. 5, no. 1, pp. 11–21, 2018, doi: 10.1016/j.matpr.2017.11.047.
[6] P. Schott, J. Sedlmeir, N. Strobel, T. Weber, G. Fridgen, and E. Abele, “A Generic Data Model for Describing Flexibility in Power Markets,” *Energies*, vol. 12, no. 10, p. 1893, 2019, doi: 10.3390/en12101893.
[7] R. Khatri, M. Schmidt, and R. Gasper, “Active participation of industrial enterprises in electricity markets - a generic modeling approach,” *Energy Inform*, vol. 4, S3, 2021, doi: 10.1186/s42162-021-00173-5.
[8] E. Corsetti, S. Riaz, M. Riello, and P. Mancarella, “Modelling and deploying multi-energy flexibility: The energy lattice framework,” *Advances in Applied Energy*, vol. 2, p. 100030, 2021, doi: 10.1016/j.adapen.2021.100030.
[9] M. Geidl and G. Andersson, “A modeling and optimization approach for multiple energy carrier power flow,” in *2005 IEEE Russia Power Tech*, St. Petersburg, Russia, 2005, pp. 1–7.
[10] T. Krause, G. Andersson, K. Fröhlich, and A. Vaccaro, “Multiple-Energy Carriers: Modeling of Production, Delivery, and Consumption,” *Proc. IEEE*, vol. 99, no. 1, pp. 15–27, 2011, doi: 10.1109/JPROC.2010.2083610.
[11] K. Heussen, S. Koch, A. Ulbig, and G. Andersson, “Energy storage in power system operation: The power nodes modeling framework,” in *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, Gothenburg, Sweden, 2010, pp. 1–8.
[12] F. R. Albogamy *et al.,* “Efficient Energy Optimization Day-Ahead Energy Forecasting in Smart Grid Considering Demand Response and Microgrids,” *Sustainability*, vol. 13, no. 20, p. 11429, 2021, doi: 10.3390/su132011429.
[13] M. Brennenstuhl, D. Lust, D. Pietruschka, and D. Schneider, “Demand Side Management Based Power-to-Heat and Power-to-Gas Optimization Strategies for PV and Wind Self-Consumption in a Residential Building Cluster,” *Energies*, vol. 14, no. 20, p. 6712, 2021, doi: 10.3390/en14206712.
[14] M. Kopp, “Strommarktseitige Optimierung des Betriebs einer PEM-Elektrolyseanlage,” Dissertation, Universität Kassel, Kassel, 2018.
[15] M. Majidi, S. Nojavan, and K. Zare, “Multi-Objective Optimization Framework for Electricity and Natural Gas Energy Hubs Under Hydrogen Storage System and Demand Response Program,” in *Operation, Planning, and Analysis of Energy Storage Systems in Smart Energy Hubs*, B. Mohammadi-Ivatloo and F. Jabari, Eds., Cham: Springer International Publishing, 2018, pp. 425–446.
[16] F. Najibi, T. Niknam, and A. Kavousi-Fard, “Optimal stochastic management of renewable MG (micro-grids) considering electro-thermal model of PV (photovoltaic),” *Energy*, vol. 97, pp. 444–459, 2016, doi: 10.1016/j.energy.2015.12.122.
[17] D. Wang *et al.,* “An energy-constrained state priority list model using deferrable electrolyzers as a load management mechanism,” *Applied Energy*, vol. 167, pp. 201–210, 2016, doi: 10.1016/j.apenergy.2015.10.129.
[18] F. Zhu, J. Fu, P. Zhao, and Da Xie, “Robust energy hub optimization with cross - vector demand response,” *Int Trans Electr Energ Syst*, vol. 30, no. 10, 2020, doi: 10.1002/2050-7038.12559.
[19] W. Li, T. Zhang, and R. Wang, “Energy Management Model of Charging Station Micro-Grid Considering Random Arrival of Electric Vehicles,” in *2018 IEEE International Conference on Energy Internet (ICEI)*, Beijing, China, 2018, pp. 29–34.
[20] G. Lorenzi and C. A. S. Silva, “Comparing demand response and battery storage to optimize self-consumption in PV systems,” *Applied Energy*, vol. 180, pp. 524–535, 2016, doi: 10.1016/j.apenergy.2016.07.103.
[21] Y. Shen, W. Hu, M. Liu, F. Yang, and X. Kong, “Energy storage optimization method for microgrid considering multi-energy coupling demand response,” *Journal of Energy Storage*, vol. 45, p. 103521, 2022, doi: 10.1016/j.est.2021.103521.
[22] S. A. F. Asl, L. Bagherzadeh, S. Pirouzi, M. Norouzi, and M. Lehtonen, “A new two-layer model for energy management in the smart distribution network containing flexi-renewable virtual power plant,” *Electric Power Systems Research*, vol. 194, p. 107085, 2021, doi: 10.1016/j.epsr.2021.107085.
[23] C. Li, X. Jia, Y. Zhou, and X. Li, “A microgrids energy management model based on multi-agent system using adaptive weight and chaotic search particle swarm optimization considering demand response,” *Journal of Cleaner Production*, vol. 262, p. 121247, 2020, doi: 10.1016/j.jclepro.2020.121247.
[24] J. Mikkola and P. D. Lund, “Modeling flexibility and optimal use of existing power plants with large-scale variable renewable power schemes,” *Energy*, vol. 112, pp. 364–375, 2016, doi: 10.1016/j.energy.2016.06.082.
[25] P. Bakhshaei, A. Askarzadeh, and R. Arababadi, “Operation optimization of a grid-connected photovoltaic/pumped hydro storage considering demand response program by an improved crow search algorithm,” *Journal of Energy Storage*, vol. 44, p. 103326, 2021, doi: 10.1016/j.est.2021.103326.
[26] D. Rakipour and H. Barati, “Probabilistic optimization in operation of energy hub with participation of renewable energy resources and demand response,” *Energy*, vol. 173, pp. 384–399, 2019, doi: 10.1016/j.energy.2019.02.021.
[27] A. Rinaldi, M. C. Soini, K. Streicher, M. K. Patel, and D. Parra, “Decarbonising heat with optimal PV and storage investments: A detailed sector coupling modelling framework with flexible heat pump operation,” *Applied Energy*, vol. 282, B, p. 116110, 2021, doi: 10.1016/j.apenergy.2020.116110.
[28] S. Cao and K. Sirén, “Impact of simulation time-resolution on the matching of PV production and household electric demand,” *Applied Energy*, vol. 128, pp. 192–208, 2014, doi: 10.1016/j.apenergy.2014.04.075.

[29] T. Unger and S. Dempe, *Lineare Optimierung*. Wiesbaden: Vieweg+Teubner, 2010.

[30] EPEX SPOT SE, Ed., “IntraDay Auction Prices for Germany,” Accessed: Aug. 23 2022. [Online]. Available: www.epexspot.com

[31] C. Derksen and R. Unland, “The EOM: An Adaptive Energy Option, State and Assessment Model for Open Hybrid Energy Systems,” in *Proceedings of the 2016 Federated Conference on Computer Science and Information Systems*, 2016, pp. 1507–1515.

[32] IBM Corporation, *IBM ILOG CPLEX Optimizer (V22.1.0).* [Online]. Available: https://www.ibm.com /academic/topic/data-science (accessed: Aug. 23 2022).

[33] D. Gusain, M. Cvetkovic, R. Bentvelsen, and P. Palensky, “Technical Assessment of Large Scale PEM Electrolyzers as Flexibility Service Providers,” in *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*, Delft, Netherlands, 2020, pp. 1074–1078.

Registration of Images with widely varying Focal Lengths for Quality Inspection of Aircraft Components

Marvin Höhner, Fabian Stoller, Milapji Singh Gill, Alexander Fay
Institute of Automation Technology
Helmut Schmidt University Hamburg
Hamburg, Germany
marvin.hoehner@hsu-hh.de

***Abstract* – Reliable quality inspection of aircraft components to identify defects is an essential process step for maintenance, repair and overhaul (MRO) service providers to ensure safe flight operations. Currently, highly experienced employees inspect and check fine-granular substructure parts of components manually from different perspectives by using a microscope. Methods from image processing and machine learning offer the potential to automate and accelerate this process step without reducing the quality of the inspection. For this purpose, a camera with a wide-angle lens is needed first to capture the entire sub-component. In addition, a microscope camera is required for detailed observation of finer parts and the identification of defects. The aim is to be able to spatially locate the detailed information from the microscope image in an overview image. Accordingly, this overview image can be used by the employee for troubleshooting. In this context image registration is not a trivial task considering the huge difference in focal lengths of both cameras and the corresponding difference in recorded detail. In the following contribution, a two-stage concept for image registration in quality inspection tasks for aircraft components will be presented to overcome this obstacle. An evaluation of this approach was performed using a demonstrator for the inspection of certain aircraft sub-components.**

Keyword – Image Processing, Image Registration, Quality Inspection, Aviation, MRO

I. Introduction

The quality inspection of aircraft components in the field of maintenance to identify defects is an important work step that places considerable demands on the respective MRO-service providers [1]. Highly trained and experienced employees are required for this time-consuming task in order to ensure appropriate quality and the safe functionality of different individual components in flight operation [1, 2]. A variety of line-replaceable units (LRUs) are characterized by a complex structure consisting of several sub-components with fine-granular similar looking parts that must be inspected with utmost attention to detail. Even the smallest deviations can lead to a malfunctioning component. Thus, a thorough quality control and inspection becomes even more important. However, a quality inspection carried out manually by the technician is quite time-consuming. In order to remain competitive and to provide customers with their components quickly and reliably, it could be advantageous to replace this process step by an automated, data-based system. Especially methods from the field of image processing and machine learning offer the potential to assist technicians with these repetitive, time-consuming tasks [2–4].

To ensure reliable detection of defects, images of the sub-components with different levels of magnification and perspectives are required. Microscopically enlarged areas of fine-granular parts are needed for an automated classification of possible defects. Furthermore, similar looking fine-granular parts already examined by the microscope should be located in an overview image with references to faulty points. These are recorded by the second camera with the wide-angle lens showing the whole sub-component. Subsequently, this overview image should be available in a final report, which is needed by the employee for troubleshooting. The transfer of information from a microscopic image to a macroscopic overview image requires that sufficient matching features are found in both images [5]. However, the very large difference in scale in this context represents a significant challenge to be solved in the field of quality inspection of aircraft components.

In the following contribution, a concept is developed which can support MRO service providers in the field of quality inspection of aircraft components in dealing with such challenges as those mentioned above. The concept has been implemented by means of a demonstrator and evaluated at various levels of complexity. The paper is structured as follows: Sec. II briefly describes the quality inspection process of aircraft components as well as elementary methods of image registration. Based on this, functional and non-functional requirements regarding the system setup and the concept are derived. Sec. III discusses related research works covering similar challenges. The two-part concept for the registration of images with varying focal lengths is presented in Sec. IV. Accordingly, Sec. V explains the implementation of the demonstrator with hardware and software components. A discussion in Sec. VI then summarizes the results from the applications that have been carried out at different levels of complexity. Sec. VII provides a final summary of the results and an outlook.

II. Background

A. *Quality Inspection of aircraft components*

The quality inspection of aircraft components is integrated into an overall process in which the causes of faults are investigated. Typically, the technician examines sub-components with their fine granular parts for possible damages which might be leading to a system failure. When inspecting such subcomponents, the technician looks for anything that deviates visually from a normal state. Depending on the workshop, the entire maintenance process of an aircraft component can be accompanied by one or several different technicians. The maintenance process includes e.g. the receipt, the visual inspection, different tests, the troubleshooting and the final decision on the release of the LRU. A quality inspection can be carried out in different stages of the maintenance process, depending on the degree of disassembly of the component. For sub-components with fine-granular similar looking parts, a microscope is used in most cases. Based on experience, areas that are particularly susceptible to faults are primarily focused on. Typically, the sub-component

https://doi.org/10.24405/14561

is inspected from multiple angles. After the inspection a decision has to be made whether a revision is needed or not. This decision is very dependent on the technician and his/her experience. Generally, the inspection of a single sub-component can be completed within a few seconds if there is either a very conspicuous or no defect. However, if cases are involved where the detection is not obvious, the decision-making process can be significantly prolonged. In any case, with several sub-components per LRU, the current process requires a considerable amount of time. On this account, an automated system could be advantageous.

B. Image Registration

Image registration is a method originating in image processing which has been applied to various problems in different domains [6, 7]. It aims to bring two or more images of the same scene taken from different positions, by different cameras or at different time instances into the best possible alignment with each other [8].

Several steps are usually necessary for a successful and precise image registration. For easier processing of the images, a rectification is needed first. Additionally, in order to eliminate the distortion, respective intrinsic camera parameters are required. These are determined by the use of calibration standards [9]. These are for example the focal length of the camera, the horizontal and vertical image size, the location of the focal point in the image plane and the distortion coefficients. Following this step, unambiguous corresponding points are searched for in both images, as far as image sections overlap [5]. These points can be assigned in different ways. A distinction is made between feature-based methods and area-based methods [8, 10]. In feature-based methods, a set of features is first extracted from both images before an attempt is made to assign them to each other [8]. Area-based methods combine the feature recognition step with finding corresponding points [10]. After finding enough corresponding points in the images, this can be used to determine a transformation matrix between these images. The number of corresponding points required depends on the complexity of the required transformation. The more points can be included in the calculation, the more precise the transformation will be. Once solved, this matrix can be used to assign any pixel from an image to the other one [5].

C. Requirements

For the specific task of image registration in the quality inspection of aircraft components, functional and non-functional requirements are gathered with regard to the concept to be developed. The requirements are divided into two subsets. The first set of functional and non-functional requirements (see TABLE I*)* addresses the system structure. These are derived from the designed overall system, its objectives as well as an observation from the process described above. The objective here is to select the relevant hardware and software components for the task of image registration and the targeted subsequent automated quality inspection (not part of this contribution).

TABLE I: FUNCTIONAL AND NON-FUNCTIONAL REQUIREMENTS.

ID	*Category*	*Requirement*
F-1	Functional	The system requires a microscope camera and a wide-angle camera to record the sub-component in various degrees of detail.
F-2	Functional	The system requires two cameras that are in a fixed position relative to each other so that the relative position of the cameras remains constant between shots.
F-3	Functional	The image section of the microscope camera must be in the image section of the wide-angle camera so that the same fine-granular part of a sub-component can be captured in both images.
F-4	Functional	The wide-angle camera must be able to record 24 images per second so that each image from the microscope camera can be assigned to the wide-angle camera.
F-5	Functional	Images taken in the same time period must be able to be matched to each other to ensure that both images depict the same scene.
F-6	Functional	The cameras must be adjustable by up to 45 degrees in any direction so that the fine-granular parts can be viewed from the side.
F-7	Functional	The working distance to the subcomponent is 100 mm, so that even subcomponents with high structures can be viewed.
F-8	Functional	The stand must be 100 mm adjustable in height so that fine-granular parts can be viewed at different heights.
NF-1	Non-Functional	The microscope camera must magnify the image 30 times in order to perform a quality inspection of fine-granular parts
NF-2	Non-Functional	The wide-angle camera must have a minimum aperture angle of 110.8 degrees so that an overview image of the sub-component can be taken.
NF-3	Non-Functional	The wide-angle camera must display 1mm x 1 mm with at least 5x5 pixels so that details can be recognized.

The second set (see TABLE II) exclusively deals with non-functional requirements, which are to be considered and evaluated in particular for the image registration concept to be developed.

TABLE II: FUNCTIONAL AND NON-FUNCTIONAL REQUIREMENTS.

ID	*Category*	*Requirement*
NF-4	Non-Functional	The system should be able to detect at least the area that the microscope camera has already observed.
NF-5	Non-Functional	It must be possible to freely hold the subcomponent under the camera in order to increase acceptance among employees.
NF-6	Non-Functional	The system should be functional regardless of the type of subcomponent.

III. RELATED WORKS

According to [11], image registration consists of five stages: Feature detection and description, feature matching, rejection of outliers, estimation of a transformation and the reconstruction of the view. The state-of-the-art feature detectors (e.g. [10, 12–14]) all come with their own descriptors. The aim here is to describe features independently from scale, rotation and affine transformation. There are, nonetheless, limitations to this claim which become obvious when registering images with hugely different spatial resolutions.

A more recently developed feature detector and descriptor is KAZE [10]. It uses nonlinear scale spaces to locally adapt the blur to the image data and reduce image noise while keeping object boundaries at the same time. This yields a higher localization accuracy. It is also invariant to rotation.

In the field of remote sensing the registration of images from different modalities like infrared or radar with different properties and resolutions is a typical challenge. The methods employed have evolved from manual point matching to automated feature-based matching and estimation of the transform [6]. The authors of [6] outline that the use of image features derived from convolutional neural network (CNN) hidden layers may yield results that are superior to the SIFT [12] features that are widely used. Albeit, the authors emphasize as well that the use of CNNs leads to challenges like the availability of training data. Especially during the quality inspection of aircraft components in the way described, tasks with a low quantity of defects on the one hand and high product variations on the other hand this is a problem.

An application that also employs a registration between cameras with vastly different properties is the registration of the field of view (FOV) of pan-tilt-zoom (PTZ) surveillance cameras onto aerial orthophotos like it is presented in [7]. The authors propose a method that is feature-based without disclosing the actual algorithm used. However, the field of view of each camera in a surveillance system is transformed onto a map-like orthophoto to simplify handling of the different cameras by users.

Basically, looking at the related works, it can be observed that a comparable approach to the one in this contribution could not be found. This may be due to the very specific requirements that have to be considered in this field. Nevertheless, the approach presented in this contribution could also be helpful for use cases in other domains (e.g. medicine).

IV. Concept for Image Registration in Quality Inspection of Aircraft Components

With those challenges and requirements in mind a novel method for bridging the difference in focal lengths has been developed. The approach consists of two steps in order to register the images of a microscopic camera onto a macroscopic image containing the complete part under scrutiny.

A. *Two Step Concept*

Preliminary tests have shown that the direct registration from the microscopic camera onto the macroscopic wide-angle overview image seems hardly possible. Therefore, an intermediate image with an intermediate magnification is introduced. The camera capturing this intermediate image and the microscope camera are in fixed relative positions. Accordingly, only their joint relative position with respect to the object may vary. The microscopic camera with a nearly telecentric lens, however, has a very narrow window where the images captured are sufficiently sharp for further image processing. Consequently, the distance of the object, the sub-component under inspection, from the cameras is assumed to be nearly constant. The position of the microscope camera's FOV in relation to the coordinates of the intermediate camera can be determined by matching key points of a known calibration pattern. We used the corner points of a checkerboard pattern visible in both cameras images to determine a transformation between the coordinates of the two cameras.

Subsequently, the second step is the registration of the image taken by the intermediate camera onto the overview image of the complete part under investigation that has been taken before the inspection. This can be conducted using the state-of-the-art in feature-based image registration. Further preliminary tests with the state-of-the-art feature detectors and descriptors SIFT [12], BRISK [15] and KAZE [10] have shown that KAZE features have a superior performance in preliminary experiments with regard to the requirements.

B. *Transformation Matrix M1*

The first step of the two-step registration method is conducted before the actual inspection. The matrix $M1$ describes the transformation from coordinates of the microscopic camera to the coordinates of the intermediate camera. It should be mentioned that $M1$ is constant due to the likewise constant relative positions of the cameras. As long as the internal camera parameters (such as focus or magnification) or the relative position of the cameras to each other are not changed, recalibration is not necessary.

As the intermediate camera is a wide-angle camera with a rather short focal length, the image captured underlies rather intensive distortion by the camera's optics. In order to undistort the images, a single camera calibration is performed using an asymmetric checkerboard pattern as well (see [16]). The microscopic camera does not need to be undistorted because of its telecentric optics. After the wide-angle camera's images have been undistorted, an asymmetric checkerboard pattern is placed in the FOV of the microscopic camera and the wide-angle camera at the same time. The corner points of the checkerboard fields are determined as corresponding points in both views and subsequently used for estimating the transformation $M1$. The complete procedure for the computation of $M1$ is described in FIGURE 1.

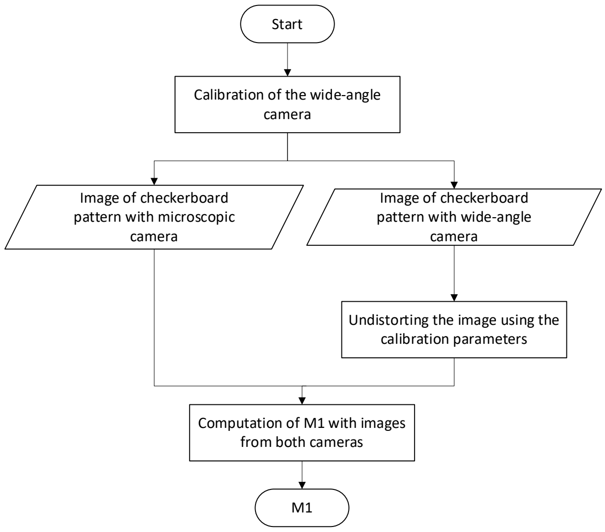


FIGURE 1: FLOW DIAGRAM OF THE PROCEDURE FOR ESTIMATING M1.

C. *Transformation Matrix M2*

For the registration of images from the wide-angle camera with the overview image, taken before the inspection process, a feature-based approach to calculating the transformation matrix $M2$ is chosen. With the Matrix $M2$ a transformation of coordinates from the wide-angle camera into the overview image's coordinate system is enabled. As mentioned before, preliminary experiments yield that KAZE is the most suitable feature detection and description algorithm from the state-of-the-art. In these preliminary tests it exhibits a considerably more reliable registration than SIFT and BRISK. For detecting and rejecting outliers from the set of matched features between the two images MSAC [17] is employed. After outlier rejection the remaining inliers are used for an estimation of the transformation matrix $M2$. This transformation needs to be calculated for every newly taken image. This is due to the fact that the position of the sub-component will change between images when held by a person. Consequently, the same applies to $M2$.

The complete transformation of the points in the microscopic camera's images onto the overview image taken of the whole sub-component before the actual inspection is thus a subsequent application of $M1$ and $M2$. In this regard $M1$ is being fixed during the inspection and $M2$ is changing with every image taken. Using these transformations, the areas and even single fine-granular and similar-looking parts found to be faulty can be marked in the overview image.

V. IMPLEMENTATION

Based on the preliminary considerations described, the implementation of the demonstrator, consisting of hardware and software components, is described below. In this context, the functional requirements F-1 to F-8 and the non-functional requirements NF-1 to NF-3 are considered (see TABLE II and II).

A. Hardware

The algorithm described in the previous section has been implemented in a semi-automated inspection system for quality inspection. FIGURE 2 depicts the overall system. The most important detail of the implementation is that the cameras are mounted in a parallel position. Also, they should be mounted as close to each other as possible. Both helps to minimise errors caused by deviations of the object from its assumed constant distance to the cameras.

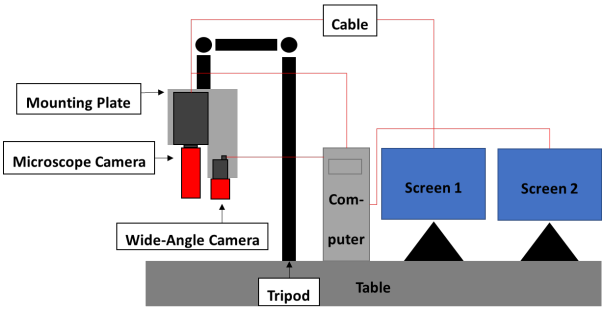


FIGURE 2 OVERVIEW OF THE SYSTEM SETUP WITH TWO CAMERAS AND TWO DISPLAYS.

The microscopic camera uses a Gigabit Ethernet connection for data transfer and the wide-angle camera is interfaced using USB. Both have their own monitor for displaying the current image feed or the accumulated information gathered for simplifying the inspection for tiny faults. The working distance of the microscopic camera is $100mm$ and the wide-angle camera has a minimal working distance of $37mm$, respectively. The resolution of the wide-angle camera is chosen so that it resolves small details sufficiently. This also supports the stereo calibration of the two cameras by displaying the calibration points with higher precision. The calibration itself is conducted using an 8x7 checkerboard with squares of $2mm$ width and height each. The components have been chosen in order to fulfil the requirements described earlier.

B. Software

On the basis of these hardware components the two-step algorithm for registering the microscopic camera with an overview image taken of the complete part under inspection has been implemented using MATLAB 2021b. The cameras are interfaced using their respective Python-based APIs so that the prototypical implementation does not run online. Because especially the microscopic camera has only a narrow region where it produces sharp images, NIQE [18] is used as an image quality metric to filter out images of insufficient quality before the actual registration process [19].

VI. DISCUSSION

The system presented must meet the requirements discussed previously. Therefore, the demonstrator has been tested at three different levels of complexity. This aims to verify whether the system meets the performance-related requirements NF-4 and NF-5. Furthermore, the performance of the two-stage concept is to be evaluated. Performance in this context is assessed using the deviation of test points transformed from the microscopic image to the overview image from the real points in the overview image. The ground truth positions of points in the overview image have been determined manually. As a test object an artificial geometric pattern printed on a rigid board has been used to mimic an aircraft component. The board has test points distributed all over it. The test board is displayed in FIGURE 3. For a final evaluation an actual component with similar-looking fine-granular parts has been used.

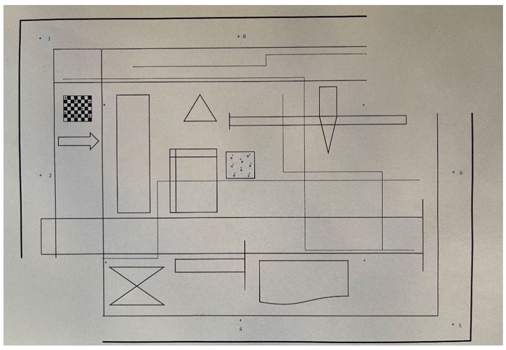


FIGURE 3 TEST BOARD WITH GEOMETRIC PATTERNS AND DISTRIBUTED TEST POINTS.

A. Evaluation using a static perpendicular scene

The first tests are conducted with a static setup. Consequently, the test board remains in a fixed position during image capture. The position of the test object is approximately perpendicular in front of the two cameras. The system is set up in a way that the cameras can capture sharp images of the test object. The wide-angle camera is calibrated and the transformation $M1$ is computed in compliance with FIGURE 1 before the actual image capturing. The test board is captured in several different but static positions.

TABLE III shows the overall results from those experiment. The proposed two-step algorithm exhibits a mean error of $0.8377px$ and a standard deviation of the error of $0.4220px$ in the wide-angle images. Here, $6.5px$ correspond to a distance of $1mm$. Also, TABLE III demonstrates qualitatively that the errors resulting from each step of the registration are not oriented equally. In FIGURE 4 the steps of the registration of the test points are displayed using 3 images. In the result image on the right the error of the registration is illustrated with blue circles showing the assumed ground truth and the red dots showing the estimated location. The total error is, hence, not significantly larger than the errors in each of the two steps. The overall error is sufficiently small with respect to the distribution of the fine-granular parts. It is in the submillimetre range depending on the distance from which the overview image is taken in a particular case. Consequently, it is possible to mark single fine-granular parts found in the microscopic camera in the overview image with considerable accuracy. Accordingly, NF-4 is fulfilled to a high degree.

FIGURE 4 EVALUATION OF THE PRECISION OF THE REGISTRATION USING A TEST PATTERN.

TABLE III: ERRORS OF THE CALCULATED MATRICES M1, M2 AND THE OVERALL TRANSFORMATION M1*M2 WITH THE TEST OBJECT LYING ON A TABLE.

Error E	$M1$	$M2$	$M1$ & $M2$
Mean error μ_e in px	0.8377	0.6779	0.9065
Standard deviation of the error σ_e in px	0.4220	0.3436	0.4756
Maximum error E_{max} px	2.1656	1.7457	2.2273

B. Evaluation with varying distance

The second level of the evaluation focusses on the error when varying the distance of the test board from the cameras. This distance is assumed to be constant so that $M1$ does not need to be recalculated for every image.

The results in TABLE VI show the measured errors with the test board at different distances. Deviations are setup in a range of $-5mm$ to $5mm$ from the optimal distance of $100mm$ from the microscopic camera. As expected, the errors increase with increasing deviation from the optimal working point. The errors increase faster when increasing the distance from the camera as compared to decreasing the distance. Also, the relatively constant distribution of the error around its mean confirms that this is a systematic error.

The use of NIQE [18] for image quality estimation assesses only images taken within a range of $-1mm$ to $2mm$ as sufficient for further processing. For this distance, the mean errors are $2.9059px$ and $4.6809px$, respectively. This is equivalent to a total deviation from the ground truth of less than $1mm$ as measured on the test board in the wide-angle image. These findings support that the requirement NF-4 is fulfilled. And even more so, because it is possible to not only mark the region but even fine-granular parts in the overview image with considerable accuracy.

TABLE VI: ERROR RESULTING FROM THE VARIATION OF THE DISTANCE OF THE OBJECT FROM THE CAMERA.

Deviation from focal distance in mm	Mean error μ_e in px	Standard deviation σ_e in px	Maximum error in px
-5	12.7711	0.9267	14.9429
-4	9.5361	0.9119	11.5441
-3	7.5892	0.8924	8.9504
-2	5.0119	0.8963	6.8827
-1	2.9059	0.6796	3.9016
0	0.8377	0.4220	2.1656
1	2.2301	0.7510	3.9643
2	4.6809	0.8743	5.9602
3	6.2440	0.9505	7.8922
4	8.3654	1.4619	10.3148
5	11.7280	1.0494	13.0224

C. Evaluation of a manual part inspection

The final stage of the evaluation aims to replicate conditions during a real inspection of a potentially faulty part. Therefore, several continuous images are captured. In this sequence of images, an actual component with fine-granular similar-looking parts has been used as test object. The test part is positioned manually in the FOV of both cameras like it would be done during an actual inspection process. The images are therefore prone to motion blur and other insufficiencies resulting from human motion and imprecision in positioning the part.

TABLE V shows the resulting precision of the registration. The mean overall error when transforming test points from the microscopic view onto the overview is $\mu_E = 1.6023px$. Even the resulting maximum error $E_{max} = 3.2669px$ on the overview image in terms of distance is, however, still well below $1mm$ for both test objects. The absolute errors are slightly greater than those observed in the first two stages using the test board. The general distribution of the error, however, is very comparable to the experiments using the test board. Therefore, these results demonstrate compliance of the developed system to the requirements NF-4, NF-5 and even NF-6 because the proposed method is able to localize fine-granular parts in the overview for an actual part that is guided by hand and also in the geometric pattern.

TABLE V: ERRORS OF THE CALCULATED MATRICES M1, M2 AND THE OVERALL TRANSFORMATION M1*M2 FOR THE MANUAL POSITIONING WITHOUT GUIDANCE.

Error E	$M1$	$M2$	$M1 * M2$
Mean error μ_E in px	1.4320	0.8348	1.6023
Standard deviation of the error σ_E in px	0.6671	0.3987	0.8157
Maximum error E_{max} px	2.4992	1.7861	3.2669

VII. SUMMARY AND OUTLOOK

In the present contribution a method has been described to bridge the gap between cameras with widely varying focal lengths. This difference has proven to be a challenge for image registration. Especially quality inspection tasks of aircraft components manually or automated may benefit from the two-step solution. It allows to accumulate the information gained from highly detailed microscopic images on a macroscopic overview image with a wide-angle image as an intermediate step. In the practical evaluation of the method its accuracy has been demonstrated. Even under challenging circumstances with an actual person holding the component, the method demonstrated an accuracy that is high enough for localizing fine-granular parts from the microscopic imagery on the overview image. With regard to the requirements mentioned in the beginning, most of them have been fulfilled by selecting suitable components. For the requirements NF-4, NF-5 and NF-6 compliance has been demonstrated by the experiments presented.

With this two-step algorithm manual inspection tasks of aircraft components may be supported by decreasing the amount of overhead for documentation and reporting necessary to track the deficiencies. A more thorough investigation of suspicious regions of the inspected parts is made possible by the increased amount of time available to the inspection worker. Due to faster inspection and documentation, this system is a first step towards the full automation of such manual inspection tasks. With the ability to locate the currently inspected components on the part, automated inspection systems may infer where to look for defects and fix them if possible. For future research it would be interesting if this two-step approach could be further simplified by the use of a deep learning approach rather than a classic image processing pipeline as described.

ACKNOWLEDGEMENT

This paper is funded by dtec.bw – Digitalization and Technology Research Center of the German Federal Armed Force [ProMoDi].

REFERENCES

[1] C. Beltran-Gonzalez, M. Bustreo, and A. Del Bue, "External and internal quality inspection of aerospace components," in *2020 IEEE International Workshop on Metrology for AeroSpace: Virtual conference, 22-24 June 2020 : proceedings*, Pisa, Italy, M. Marracci and A. Buffi, Eds., 2020, pp. 351–355, doi: 10.1109/MetroAeroSpace48742.2020.9160103.

[2] S. Martelli *et al.,* "Deep Endoscope: Intelligent Duct Inspection for the Avionic Industry," *IEEE Trans. Ind. Inf.*, vol. 14, no. 4, pp. 1701–1711, 2018, doi: 10.1109/TII.2018.2807797.

[3] M. Heizmann *et al.,* "Implementing machine learning: chances and challenges," *at - Automatisierungstechnik*, vol. 70, no. 1, pp. 90–101, 2022, doi: 10.1515/auto-2021-0149.

[4] Y. D. Yasuda, F. A. Cappabianco, L. E. G. Martins, and J. A. Gripp, "Aircraft visual inspection: A systematic literature review," *Computers in Industry*, vol. 141, p. 103695, 2022. doi: 10.1016/j.compind.2022.103695. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0166361522000926

[5] R. Szeliski, *Computer Vision: Algorithms and Applications* (SpringerLink Bücher). London: Springer London, 2011.

[6] S. Dawn, V. Saxena, and B. Sharma, "Remote Sensing Image Registration Techniques: A Survey," in 2010, pp. 103–112, doi: 10.1007/978-3-642-13681-8_13.

[7] J. W. Davis, "Camera Control and Geo-Registration for Video Sensor Networks," in *Distributed Video Sensor Networks*, B. Bhanu, Ed., London: Springer London Limited, 2011, pp. 247–257. [Online]. Available: https://link.springer.com/chapter/10.1007/978-0-85729-127-1_17

[8] B. Zitová and J. Flusser, "Image registration methods: a survey," *Image and Vision Computing*, vol. 21, no. 11, pp. 977–1000, 2003, doi: 10.1016/S0262-8856(03)00137-9.

[9] Z. Zhang, "Flexible camera calibration by viewing a plane from unknown orientations," in *The proceedings of the Seventh IEEE International Conference on Computer Vision: September 20 - 27, 1999, Kerkyra, Greece*, Kerkyra, Greece, 1999, 666-673 vol.1, doi: 10.1109/ICCV.1999.791289.

[10] P. F. Alcantarilla, A. Bartoli, and A. J. Davison, "KAZE Features," in 2012, pp. 214–227, doi: 10.1007/978-3-642-33783-3_16.

[11] S. A. K. Tareen and Z. Saleem, "A comparative analysis of SIFT, SURF, KAZE, AKAZE, ORB, and BRISK," in *2018 International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*, 2018, doi: 10.1109/icomet.2018.8346440.

[12] D. G. Lowe, "Distinctive Image Features from Scale-Invariant Keypoints," *International Journal of Computer Vision*, vol. 60, no. 2, pp. 91–110, 2004. doi: 10.1023/B:VISI.0000029664.99615.94. [Online]. Available: https://link.springer.com/article/10.1023/b:visi.0000029664.99615.94

[13] P. Alcantarilla, J. Nuevo, and A. Bartoli, "Fast Explicit Diffusion for Accelerated Features in Nonlinear Scale Spaces," in *Procedings of the British Machine Vision Conference 2013*, 2013, doi: 10.5244/c.27.13.

[14] H. Bay, T. Tuytelaars, and L. van Gool, "SURF: Speeded Up Robust Features," in *Computer vision - ECCV 2006: 9th European Conference on Computer Vision, Graz, Austria, May 7 - 13, 2006; proceedings* (Lecture notes in computer science 3951), A. Leonardis, H. Bischof, and A. Pinz, Eds., Berlin: Springer, 2006, pp. 404–417.

[15] S. Leutenegger, M. Chli, and R. Y. Siegwart, "BRISK: Binary Robust invariant scalable keypoints," in *2011 International Conference on Computer Vision*, 2011, doi: 10.1109/iccv.2011.6126542.

[16] Z. Zhang, "A flexible new technique for camera calibration," *IEEE Trans. Pattern Anal. Machine Intell.*, vol. 22, no. 11, pp. 1330–1334, 2000, doi: 10.1109/34.888718.

[17] P. Torr and A. Zisserman, "MLESAC: A New Robust Estimator with Application to Estimating Image Geometry," *Computer Vision and Image Understanding*, vol. 78, no. 1, pp. 138–156, 2000, doi: 10.1006/cviu.1999.0832.

[18] A. Mittal, R. Soundararajan, and A. C. Bovik, "Making a "Completely Blind" Image Quality Analyzer," *IEEE Signal Process. Lett.*, vol. 20, no. 3, pp. 209–212, 2013, doi: 10.1109/lsp.2012.2227726.

[19] M. Höhner, "Konzeptionierung und Implementierung einer Pipeline zu qualitätsbasierten Auswahl von Einzelbildern aus einem fortlaufenden Strom an Bildern," Laboratory Project, Helmut Schmidt University/University of the Federal Armed Forces, Hamburg, 2022.

Application potentials of Semantic Technologies for Digital Twins in Aircraft Design, Manufacturing and Maintenance

Milapji Singh Gill, Jonathan Reif, Tom Jeleniewski, Maximilian Weigand, Alexander Fay
Institute of Automation Technology, Helmut Schmidt University
Hamburg, Germany
{milapji.gill, jonathan.reif, tom.jeleniewski, maximilian.weigand, alexander.fay} @hsu-hh.de

***Abstract* – The digital twin (DT) is a lifecycle-spanning concept applied for the systematic management and efficient use of digital artefacts (data and models) associated to individual entities or entire system networks in the course of digitalisation. A multitude of data and models related to an aircraft with its components, processes and resources are collected during the design, manufacturing, operation and maintenance. The integration of such digital artefacts can, in turn, contribute to making workflows more effective and efficient in different lifecycle phases. However, such approaches usually fail due to the large number of different heterogeneous information silos and the difficulties in linking them with each other. In this context, semantic technologies (ST) have the potential to counteract such problems and to increase interoperability as well as reusability. The aim of this paper is to present the application potentials of ST for DTs of aircrafts with their components and systems in the life cycle phases design, manufacturing and maintenance. For this purpose, typical digital artefacts and the use of ontologies for the efficient management in DTs are described. In the first step, each life cycle phase is considered separately with its data and models for products, processes and resources, together with a description of the application potentials. In the second step, cross-life cycle application potentials are described.**

Keyword – Digital Twins, Data Management, Semantic Technologies, Aviation

I. Introduction

The increasing digitisation enables the integration and networking of different information sources with the aim to accelerate and improve inefficient, time-consuming processes [1]. In this context, the DT is gaining popularity in a wide range of domains [2–4]. The approach pursued for DTs is to map a digital representation of a product, a resource or even an entire process, including its behaviour, structure and functions, on the basis of a continuous data flow [5, 6]. The integrated data can then be used in combination with application-specific models to answer descriptive, diagnostic, predictive and prescriptive questions [3].

The use of DTs in the field of aviation offers potentials in a wide variety of use cases [7–9]. As described in Fig. 1, a large amount of data and models are generated and used in design, manufacturing, operation and maintenance throughout the life cycle of an aircraft and its individual components and systems [5-7]. However, the integration of these digital artefacts into the DT poses huge challenges. The prerequisite for the targeted use, networking and interoperability of DTs is the elimination of the prevailing information silos among the companies and life cycles involved. Isolated data must be combined in a semantically consistent manner to provide a uniform view of the systems, so that a simple access as well as a correct interpretation is enabled [1, 10]. Additionally, standardised interfaces are necessary to initiate an exchange of information between different partners in the value chain [3, 4, 11]. Proprietary approaches, such as those often found in the field of aviation, are contrary to this target. Ontologies from the field of symbolic artificial intelligence (AI) are a suitable means for formally describing the semantics of a domain as well as for linking existing information [1, 3, 10, 12]. In addition, they offer the possibility of generating considerable added value from data through the purposeful combination with other digital models (e.g. from the field of sub-symbolic AI or simulation models) [3, 4].

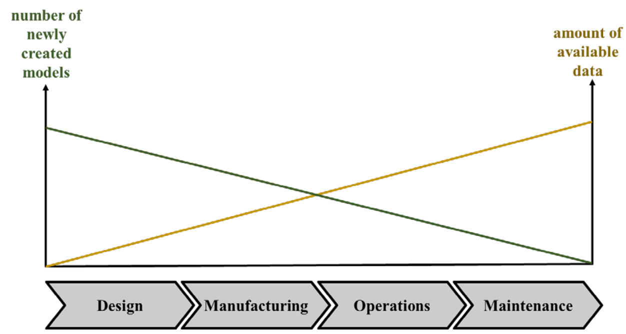


Fig. 1: Creation of models and data throughout the lifecycle of an aircraft, inspired by [3].

In the context of this contribution the application potentials of ST for DTs in different life cycle phases are analysed. For this purpose, Sec. II first introduces definitions and basic explanations of the DT and ST. Subsequently, related works on DTs in the field of aviation are discussed in Sec. III. Additionally, approaches of using ST in DTs as well as the benefits are outlined. Sec. VI. presents various application potentials of ST for DTs in the aviation domain. In this course, the individual phases of aircraft design, manufacturing and maintenance are examined in terms of data and models according to the product, process and resource principle. In this regard, different use cases are considered for the respective phases. In addition, the application potentials for the cross-lifecycle combination of data and models by using ST are presented. Sec. V summarises the contribution and provides an outlook on ongoing and future research activities.

https://doi.org/10.24405/14562

II. Background

Sec. II is intended to provide the background for this contribution. Therefore, definitions of the DT as well as a short description of ST are introduced.

A. Digital Twins

A number of definitions for the DT have accumulated over time, varying in some level of detail. A consensus among publications, in the endeavour to define the DT, is that a distinction should be made between a physical and a virtual space [5, 13]. In this case, the DT is part of the virtual space. The connection to and synchronisation with the counterpart in the physical space is created via a data flow [5]. DTs can be created from products, processes or resources that can interact with each other through defined interfaces [4, 6]. Grieves et al. [13, 14] emphasise that the DT is suitable to manage models and data of a physical assets over the entire life cycle. A DT can in turn be used to answer various questions and improve processes, as mentioned in the introduction. There are different views on the designation of the various components or digital artefacts the DT should consist of. For example, Kritzinger et al. [5] distinguish between digital models, digital shadows and DTs, depending on the degree of integration realised by an automatic or manual data flow. The DT as the ultimate state of development is characterised by a bidirectional automatic data flow between physical and virtual space. A less rigorous definition of DTs is pursued by Stark et al. [15]: An automatic data flow back to the physical counterpart is not mandatory to be considered a DT. According to this definition, the digital shadow describes the data that is recorded during the life cycle. The digital master contains type models that are only instantiated when the physical counterpart is put into operation. Accordingly, the DT arises from the interaction of the digital shadow and the digital master. Other authors introduce further capabilities of the DT. Thus there are concepts of the 'intelligent' or the 'next generation' DT [4, 16]. Such publications include methods of AI or strive to enable interaction between different DTs.

In the context of this paper, the DT is seen as a concept characterised by the interaction of information in the digital shadow (time-dependent data) and various use case-specific digital models (see Fig. 2) in order to calculate and generate valuable new data. If an information model is added to the DT, an information flow (arrows in Fig. 2) between these individual components respectively digital artefacts occurs. This is realised via various interfaces to the physical but also to the virtual space (information exchange with other DTs) [11].

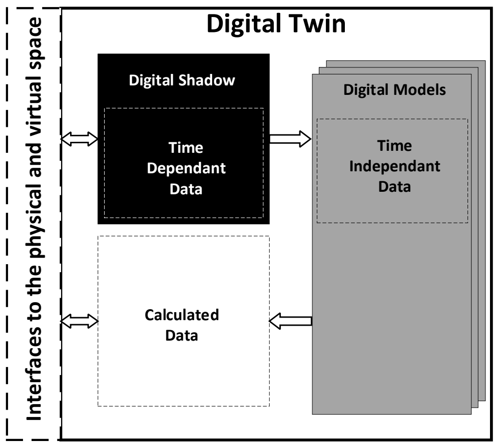


Fig. 2: DT with its digital artefacts, according to [11].

B. Semantic Technologies

In the era of Industry 4.0, a huge amount of data is generated that contains potentially valuable knowledge. However, solely raw data is of no use as long as no meaning is added. To obtain important information from and enable interoperability between the DT and its digital artefacts, as delineated in Sec. II, the DT must be enriched with semantics. To generate knowledge, this information must subsequently be linked by considering the relevant context [17].

Ontologies from the field of symbolic AI are a graph-based knowledge representation for the explicit specification of semantics within a domain [18]. Moreover, they are a suitable means for data management by describing information as well as its relationships to each other in a formal and machine-readable way [16, 19]. Most importantly, this facilitates the understanding of the information exchanged between the different actors managing the data for DTs [1]. ST are intended to develop and use such ontologies. For this purpose, the World Wide Web Consortium (W3C) has defined important ST standards like RDF, OWL and SWRL [18].

Various publications describe the benefits of Ontology-Based Data Integration (OBDI) and Ontology-Based Data Access (OBDA) to heterogeneous data sources, e.g. [20–22]. As such, knowledge of a domain can be formalised and contribute to the automation of partial steps in various use cases [23, 24]. In this context, Hildebrandt et al. [23] have introduced an ontology building method for Cyber-Physical systems (CPS) based on standards and norms. Beginning with an elicitation of requirements for the ontology by defining competency questions, method steps are introduced for the systematic modelling of the T-box and the A-box. The T-box describes terminological knowledge of a domain, i.e. relevant concepts and their relations. The associated A-box instantiates the T-box with different individuals, thus describing assertional knowledge [22].

III. Related Works

In Sec. III works related to the mentioned objective of this contribution will be described. On the one hand, DT approaches in the field of aviation as well as their specific use cases in different life cycle phases are considered in part *A*. On the other hand, part *B* describes the application potentials of ST for DTs in existing works and comparable domains.

A. DT in Aviation

There is a wide range of papers in the field of aviation using DTs and including digital artefacts for different applications and life cycle phases. Meyer et al. [7], for example, describe three use cases for DTs of aircraft and essential components. Firstly, a virtual product house is described, which aims to make aircraft design more efficient and cost-effective by using virtual testing and simulation-based certification. Secondly, a virtual engine is introduced in order to consider the development, design and optimisation of engine components and assemblies in varying levels of detail. Thirdly, a research aircraft with numerous DTs for various test aircraft of the German Federal Republic research centre for aeronautics and space is discussed. The superordinate result is a digital model of the aircraft and its components with all features and relevant data.

Yet other publications focus on the processes of manufacturing of aircraft components and the aircraft assembly. In [25], for example, a concept for a collaborative workplace for aircraft assembly is presented by Mhenni et al. The authors highlight the importance to conduct as many functional and dysfunctional experiments as possible with a DT connected to the physical system so that both are improved and converged. Furthermore, the relevance of the abstraction and integration of knowledge along the entire system is emphasised. In [26] the DT provides the foundation for an effective quality management and analysis of aircraft final assembly by using data mining methods. The multi-dimensional virtual model enables DT-based quality analysis and decision-making. This lays the foundation to describe and respond to the real-time state of each quality factor, thus improving the predictability and the quality analysis.

The usability of DTs is also being researched in the area of operation and maintenance of aircraft and its components. Liu et al. [8] describe how a DT of an aircraft can be used to proactively identify potential problems with its real-world counterpart at runtime. By using a combination of physics-based models and data-driven analytics predictions can be made regarding the remaining useful life of the physical asset. In [2] a case study of DTs for aircraft maintenance is conducted by Wang et al. In this context, the DT is built to reflect aircraft maintenance, repair, overhaul (MRO) processes and activities. The increasing number of sensors combined with networked systems enable the DT system to obtain detailed information about the condition of the aircraft and its components. On this basis the future behaviour can be predicted and maintenance activities can be planned. Cloud-based technology greatly improves the affordability and availability of the computing power required to run DTs of such complex machines.

Other publications focus on a cross-life cycle or cross-organisational use of DTs in the domain. In [27] it is described by Tuegel et al. how the DT will enable better management of an aircraft throughout its lifespan. In the current aircraft life prediction process, each type of physics has its own separate model. With DT integration of material state evolution models into a single unified structural model, the physical models will be seamlessly connected, just as they are connected in the physical structure. The DT provides a visual database that is directly linked to both, the structural model and the physical aircraft. Mandolla et al. [9] outline the need for a DT of the supply chain of an additive manufacturing process in the aviation domain. The target is to ensure maximum traceability and transparency of each operation performed on a component's history to verify its conformity for certification purposes. For this purpose, the blockchain technology is used for storing data in a secure, verifiable, and permanent way.

In sum, it can be stated that there are various approaches for the potential application of DTs and generated digital artefacts in the aviation industry across different stages of an aircraft and its components. However, there are huge potentials regarding the implementation of cross-lifecycle approaches. The basis is the definition of a uniform semantic of the data by using an end-to-end information model based on domain knowledge and standards. This is intended to ensure the interoperability and reusability of created digital artefacts.

B. Semantic Technologies for Digital Twins

Data management and integration in the DT by linking various data and models throughout the product life cycle is a major challenge with regard to heterogeneous data sources and the multitude of companies involved [19, 24]. Some publications from other domains show that there is already intensive research on the application potentials of ST in DTs to overcome the challenge of isolated information silos.

Singh et al. [19] present a DT ontology by defining the conceptual knowledge required for this purpose. The ontology is classified into three main parts. The physical layer describes an asset and the associated sensors. The data layer in turn represents the sensor data and the knowledge base. The models as well as the visualisation and analysis are located in the model layer. In addition, actionable insights are introduced. The linking of all these concepts serves to represent a typical information flow in a DT. The authors of [1] describe an approach for the representation of all relevant data in a supply chain for semiconductors by means of a DT. Especially, the phases of planning, development, production and delivery are taken into account. The superordinate target is the holistic digitalisation of the product life cycle through the integration of data from participating companies. For this purpose, the supply chain with its entities (e.g. products), processes and relationships are represented by means of an ontology. This enables improved collaboration between the companies. Boschert et al. [16] also emphasise the importance of using ST in order to realise 'the next generation DT'. According to the authors such a concept is particularly characterised by the semantic linking of all relevant digital artefacts (e.g. data and simulation models) along the life cycle.

In addition to data integration, ST can also be used to realise other DT capabilities. Zheng et al. [24] for example, define vision, challenges and possibilities of a cognitive DTs. In this respect, the cognitive DT is characterised by certain properties in order to autonomously perform activities. These include, among others, autonomy, cognition and continuous further development along the life cycle. To ensure these capabilities of a cognitive DT, different digital models and data must be linked semantically. ST in this context are referred to as key enabling technologies for this purpose.

The presented publications outline that the use of ST can potentially be advantageous regarding the integration and management of digital artefacts in DTs in order to achieve interoperability. This refers to use cases that aim to integrate data within one specific life cycle phase as well as to those that take cross-life cycle approaches.

IV. Application Potentials of ST for DTs in Aviation

In the following, application potentials of ST for the use in DTs for different life cycle phases of an aircraft and its components are examined. A particular focus is being placed on the phases of aircraft design, manufacturing and maintenance. In the first step, digital artefacts to be linked are observed from products, processes and resources of the respective life cycle phase. In the second step, the application potential is extended to two cross-lifecycle use cases.

A. Aircraft Design

Aircrafts are highly complex products, due to their physical size and the number of engineering disciplines involved in their design. Apart from conventional, mechanical components, recent developments in information technology (IT) are integrated in modern aircrafts. This further increases the system complexity of the aircraft. The incorporation of DTs in early lifecycle phases, like product design, can be beneficial in many respects [14]. For example, the created DTs can be reused and extended during subsequent lifecycle phases of manufacturing, operation or maintenance [2, 8, 16]. Also, DTs incorporated during product design, can be used to derive an appropriate manufacturing process and production system design with necessary resources. As mentioned before, a key factor that enables different users and applications to reuse the data, models and services from aircraft DTs is clear and unambiguous semantics.

In modern aircraft design, the complexity of future aircraft is often tackled by implementing Model-Based Systems Engineering (MBSE). Within the aviation industry, MBSE has been adopted early and prevails as an established practice [28]. Following this approach, the product design consists of a high-level product architecture that is decomposed into structural, functional and behavioural sub-models. In addition, these can also be refined into further sub-models. While models can theoretically be refined indefinitely, MBSE relies on formal specification languages, mostly SysML, and is often limited to architectural and static views. Complex physical behaviour, including structural, electromechanical or fluid-dynamical aspects, are not within the scope of MBSE. However, these disciplines create important artefacts to the design of an aircraft. Consequently, models describing this physical behaviour as well as architectural models should be part of the descriptive part of a DT. MBSE tools can be used for both, defining the architecture of systems and creating references to external, more detailed models. The latter is necessary if static models are not sufficient to describe certain aspects.

While simple references to models can be informational for users, implemented interfaces to these models in order to use them efficiently are needed by several applications. This requires the semantics of these models and the information they contain to be explicitly defined e.g. by using ontologies. In this context ODBI can be used to integrate data, models and services within a DT for aircraft production [29].While ontologies can be used as a meta-layer in order to integrate the components of the DT, the actual data must be exchanged to be operational. Existing OBDA approaches offer access to different data sources. Furthermore, access methods to new data sources, as MBSE data [20], are being developed and can be used for semantically enriched data exchange within a DT or between DTs.

B. Aircraft Manufacturing

Current efforts in aviation have focused on reducing fuel consumption and thus also on reducing CO_2 emissions. A major contribution to this is made by weight reduction through the use of lightweight components that are manufactured from carbon fiber composites. In addition to the established production process that uses an autoclave, an alternative, resin transfer molding (RTM), is now being considered to produce those parts due to its cost efficiency. Currently, the production of large critical components using RTM processes is still at a research stage. The quality of components produced by these processes is highly dependent on selected process parameters and requires expert knowledge and parameter monitoring [30]. Typically, only a few experts possess this implicit knowledge. Furthermore, it is not accessible, neither for other employees nor machines or control algorithms. Consequently, there is a need for approaches to formalise such implicit knowledge explicitly in order to make it available for other applications. Apart from this, information on products, their production processes and used technical resources is often only available in heterogeneous data structures. For these reasons, it is difficult to contextualise information from different sources, both manually and automatically. In order to test different parameter and material combinations and their properties, a large amount of data and knowledge must be used, which is usually stored in a decentralised system. Furthermore, simulations and models (e.g. for injection processes) are used for process and RTM tool design in order to predict performance and quality of composite components as accurately as possible. Furthermore, such digital artefacts are useful as a means to expand the existing knowledge base. However, the selection of suitable algorithms for simulation-based optimisation is not a trivial task [31].

ST, as described in Sec. II and III, are suitable to overcome these challenges. From the process DT with its knowledge base, information and inferred knowledge about composite components, process configurations and required resources can be queried centrally. This also reduces the number of different software interfaces and simplifies the entire architecture and its maintenance. The expert knowledge, formalised in the ontology also lays the basis for further AI applications. One possible application with great potential for formalised expert knowledge in a machine-readable format and process rules is the use in algorithms for process control and monitoring. This offers the possibility of predictive quality assurance by detecting process deviations in the virtual process during operation and accelerated initiation of corrective measures. Moreover, maintenance activities on the machines can also be determined and planned more precisely in advance. Statements on process and product quality can be made by recording and evaluating the quality-relevant process values. Likewise, such evaluations in combination with further plant information lead to an assessment of the resources involved, so that the transition from corrective to condition-oriented maintenance can be made. Another application potential is the use of the process DT to partially perform process engineering. Normally this task is very costly in the physical world due to long process time and expensive RTM tools. Mapping these processes in the virtual space offers many advantages. One example is the virtual commissioning, in which a wide variety of process parameters can be tested in advance in the virtual space. In addition, it is also possible to simulate different process scenarios and compare the results without the process having to exist in the physical space beforehand.

C. Aircraft Maintenance

In the field of aircraft maintenance, DTs with life cycle information, as examined in related works, can be an important support for several use cases. Especially in the field of diagnosis and predictive maintenance, there is a huge need to use various data generated from sensors during operation of the aircraft as well as from the several maintenance workshops [2]. On this data basis and by considering the relevant context, different modelling approaches (e.g. high-fidelity simulation, machine learning models), can be applied for diagnosis tasks to ensure safe operation. Furthermore, an accurate and early diagnosis can significantly improve several maintenance planning tasks. Specifically, maintenance workshops are characterised by uncertainty due to a wide variety of reasons. One major factor is the lack of information about the condition of individual components or entire systems when they have arrived in the workshop [32].

Nevertheless, the use of such DTs in the field of aircraft maintenance is far from being established. One major reason is the heterogeneous data, from flight operations as well as from maintenance workshops. A large number of different data in a wide variety of formats and structures is collected by sensors during the aircraft operation. The same applies to the data sources from the workshop with potentially relevant information on components, the maintenance activities carried out (e.g. fault symptoms, fault causes, troubleshooting) and technical resources (e.g. test benches with series of measured values). The documentation of fault symptoms, causes and successful countermeasures, for example, is recorded in unstructured form, mostly in texts, by the technicians in different workshops. In addition, as in manufacturing, there are a large number of technicians with huge expert knowledge, which is currently not used in a formalised way. If these employees leave the company, maintenance companies run the risk of losing valuable knowledge.

In this respect, ontologies can be used for a wide variety of use cases and goals. OBDI and OBDA to different data sources on the basis of domain-specific concepts would have the advantage that diagnosis tasks could be carried out more effectively and efficiently. For example, fault classification tasks using classical sub-symbolic AI methods could benefit from added context to the data and prior knowledge in order to improve the accuracy of the results. This in turn would result in an improvement of maintenance planning, which could save costs. Furthermore, ontologies in combination with approaches from Natural Language Processing (NLP) offer the potential to make the recorded maintenance activities usable by computers. This in turn can be used to create assistance systems that support the employees in knowledge-intensive tasks. The ontology serves as a knowledge base in which various data is integrated. Furthermore, the expert knowledge could be formalised by using SWRL and subsequently be used for maintenance suggestions. ST enable to build a unified structure of the digital shadows of components, maintenance processes and technical resources in a reusable way.

D. Combination throughout the lifecycle

As described in the parts *A*, *B* and *C* of this section, a first useful step is to clearly define the semantics of a specific life cycle phase. In FIG. 3, the application potentials outlined from design (arrow 1), manufacturing (arrow 2) and maintenance (arrow 3) are visually depicted once again.

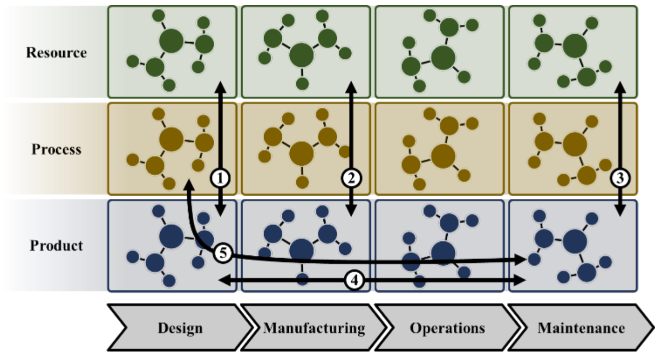


FIG. 3: APPLICATION POTENTIALS OF ST IN DIFFERENT DT LIFE CYCLE PHASES.

A particular focus in these cases, however, has been placed on the linking of digital artefacts of products (aircraft and its components), processes and resources. The ultimate goal of a DT, however, is to accompany its physical counterpart over the entire life cycle. In this contribution, the aircraft or specific individual components in particular are being accompanied. Generated digital artefacts of one phase should be reusable in different earlier or later phases. To demonstrate the added value of reusing such digital artefacts, application potentials for two further cross-lifecycle use cases are considered. Arrow 4 describes a typical application potential in the maintenance of aircraft components. For improved diagnosis, the use of high-fidelity simulation models from engineering is necessary. This allows anomalous behaviour of the component to be detected by comparing measured and calculated values. This potentially improves and accelerate the localisation of the fault causes. By semantically describing the interface to the simulation model with the required input and output variables, both data from the workshop and measured values from operation could be used even better. Moreover, there is also a great application potential the other way around as shown by arrow 5. Actually, recorded faults, fault symptoms and maintenance measures could be used retroactively in the design of components. The goal here would be to optimise the component to avoid faulty states in the operation. This in turn could have an impact on the resources and processes to be used. By using the OBDA and OBDI approaches*,* feasibility analyses for processes could be executed in the virtual space.

V. SUMMARY AND OUTLOOK

In this contribution, some application potentials of ST for DTs in the domain of aviation have been described. After considering related works, it has become evident that there is a considerable need for research in this area. ST are suitable for the integration and linking of different digital artefacts in a meaningful way. In this context, the phases of design, manufacturing and maintenance of aircraft, its components, resources and processes have been considered in order to identify some application potentials. Furthermore, it has been illustrated which life-cycle-spanning applications could be enabled by using ST.

Despite the application potentials shown, there is a considerable need for research in this area. A major obstacle is that individual companies along the life cycle are reluctant to hand over their data and models. Obviously, this is due to the fact that the shareholders involved are trying to protect their intellectual property. In this respect, research is needed into ideas on how such data can be offered as digital services. Furthermore, it is important to use established standards for the respective phases to formalise the domain knowledge. This should make the ontology comprehensible on a domain-wide basis and enable the reuse of models. Another problem is that many components of an aircraft are exchanged many times throughout its life. These dynamics must be synchronously modelled in virtual space, which is a major challenge in the field of research. The vertical and horizontal integration of DTs is still an open research issue that needs to be addressed. And last but not least data quality problems due to the large number of data handovers should not be neglected either. Only through a targeted and consistent digitisation of the entire process chain the full potential of the DT can be exploited.

ACKNOWLEDGEMENT

This paper is funded by dtec.bw – Digitalisation and Technology Research Center of the Federal Armed Forces which we gratefully acknowledge [Projects: ProMoDi, LaiLa, iMOD].

REFERENCES

[1] P. Moder, H. Ehm, E. Jofer, "A Holistic Digital Twin Based on Semantic Web Technologies to Accelerate Digitalization," in *Digital Transformation in Semiconductor Manufacturing: Proceedings of the 1st and 2nd European Advances in Digital Transformation Conference, EADTC 2018, Zittau, Germany and EADTC 2019, Milan, Italy* (Springer eBook Collection 670), S. Keil, R. Lasch, F. Lindner, and J. Lohmer, Eds., 1st ed. Cham: Springer International Publishing; Imprint Springer, 2020, pp. 3–13.

[2] T. Wang and Z. Liu, "Digital Twin and Its Application for the Maintenance of Aircraft," in *Handbook of Nondestructive Evaluation 4.0* (Springer eBook Collection), N. Meyendorf, N. Ida, R. Singh, and J. Vrana, Eds., Cham: Springer International Publishing; Imprint Springer, 2021, pp. 1–19. Accessed: Aug. 1, 2022. [Online]. Available: https://link.springer.com/content/pdf/10.1007/978-3-030-48200-8_7-1.pdf

[3] B. Vogel-Heuser, F. Ocker, I. Weiß, R. Mieth, and F. Mann, "Potential for combining semantics and data analysis in the context of digital twins," *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, early access. doi: 10.1098/rsta.2020.0368.

[4] B. Ashtari Talkhestani, T. Jung, B. Lindemann, N. Sahleb, N. Jazdi, W. Schloegl, M.Weyrich, "An architecture of an Intelligent Digital Twin in a Cyber-Physical Production System," *at - Automatisierungstechnik*, vol. 67, no. 9, pp. 762–782, 2019. doi: 10.1515/auto-2019-0039. [Online]. Available: https://www.degruyter.com/document/doi/10.1515/auto-2019-0039/html

[5] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, "Digital Twin in manufacturing: A categorical literature review and classification," *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 1016–1022, 2018. doi: 10.1016/j.ifacol.2018.08.474. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2405896318316021

[6] B. Caesar, A. Hanel, E. Wenkler, C. Corinth, S. Ihlenfeldt, and A. Fay, "Information Model of a Digital Process Twin for Machining Processes," in *2020 IEEE 25th International Conference on Emerging Technologies and Factory Automation (ETFA): Technical University of Vienna, Vienna, Austria, 08-011September 2020 : proceedings*, Vienna, Austria, 2020, pp. 1765–1772, doi: 10.1109/ETFA46521.2020.9212085.

[7] H. Meyer *et al.,* "DEVELOPMENT OF A DIGITAL TWIN FOR AVIATION RESEARCH," in online, 2020. [Online]. Available: https://elib.dlr.de/136848/

[8] Z. Liu, N. Meyendorf, N. Mrad, "The role of data fusion in predictive maintenance using digital twin," *AIP Conference Proceedings*, vol. 1949, no. 1, p. 20023, 2018, doi: 10.1063/1.5031520.

[9] C. Mandolla, A. M. Petruzzelli, G. Percoco, and A. Urbinati, "Building a digital twin for additive manufacturing through the exploitation of blockchain: A case analysis of the aircraft industry," *Computers in Industry*, vol. 109, pp. 134–152, 2019. doi: 10.1016/j.compind.2019.04.011. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0166361518308741

[10] C. Boje, A. Guerriero, S. Kubicki, and Y. Rezgui, "Towards a semantic Construction Digital Twin: Directions for future research," *Automation in Construction*, vol. 114, p. 103179, 2020. doi: 10.1016/j.autcon.2020.103179. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0926580519314785

[11] M. S. Gill, L.-T. Reiche, A. Fay, "Method for selecting Digital Twins of Entities in a System-of-Systems approach based on essential Information Attributes.," *27th IEEE International Conference on Emerging Technologies And Factory Automation (ETFA 2022)*, vol. 2022.

[12] A. Banerjee, R. Dalal, S. Mittal, K. P. Joshi, *Generating Digital Twin models using Knowledge Graphs for Industrial Production Lines*. ACM Publications, 2017. [Online]. Available: https://mdsoar.org/handle/11603/11592

[13] M. Grieves, J. Vickers, "Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems," in *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*, F.-J. Kahlen, S. Flumerfelt, and A. Alves, Eds., Cham: Springer International Publishing, 2016, pp. 85–113.

[14] M. W. Grieves, "Virtually Intelligent Product Systems: Digital and Physical Twins," in *Complex Systems Engineering: Theory and Practice*, vol. 411, S. Flumerfelt, K. G. Schwartz, D. Mavris, and S. Briceno, Eds., Reston, VA: American Institute of Aeronautics and Astronautics, Inc, 2019, pp. 175–200.

[15] R. Stark, T. Damerau, "Digital Twin," in *CIRP Encyclopedia of Production Engineering*, Springer, Berlin, Heidelberg, 2019, pp. 1–8. [Online]. Available: https://link.springer.com/referenceworkentry/10.1007/978-3-642-35950-7_16870-1?page=4

[16] S. Boschert, C. Heinrich, and R. Rosen, "Next Generation Digital Twin: Proceedings of theTwelfth International Symposium on Tools and Methods of Competitive Engineering - TMCE 2018, May 07-11, Las Palmas de Gran Canaria, Spain," 2018.

[17] M. Frické, "The knowledge pyramid: a critique of the DIKW hierarchy," *Journal of Information Science*, vol. 35, no. 2, pp. 131–142, 2009, doi: 10.1177/0165551508094050.

[18] T. I. Berners-Lee, J. Hendler, and O. R. Lassila, "THE SEMANTIC WEB," *Scientific American*, vol. 284, no. 5, pp. 34–43, 2001. [Online]. Available: http://www.jstor.org/stable/26059207

[19] S. Singh *et al.,* "Data management for developing digital twin ontology model," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 235, no. 14, pp. 2323–2337, 2021, doi: 10.1177/0954405420978117.

[20] M. Weigand, A. Fay, "Creating Virtual Knowledge Graphs from Software-Internal Data," in IECON 2022 – 48th Annual Conference of the Industrial Electronics Society, Ed., 2022.

[21] F. J. Ekaputra, M. Sabou, E. Serral, E. Kiesling, and S. Biffl, "Ontology-Based Data Integration in Multi-Disciplinary Engineering Environments: A Review," *OJIS*, vol. 4, no. 1, pp. 1–26, 2017.

[22] S. Biffl, M. Sabou, *Semantic Web Technologies for Intelligent Engineering Applications*.

[23] C. Hildebrandt *et al.,* "Ontology Building for Cyber–Physical Systems: Application in the Manufacturing Domain," *IEEE Trans. Automat. Sci. Eng.*, vol. 17, no. 3, pp. 1266–1282, 2020, doi: 10.1109/TASE.2020.2991777.

[24] X. Zheng, J. Lu, D. Kiritsis. "The emergence of cognitive digital twin: vision, challenges and opportunities." https://www.tandfonline.com/doi/epub/10.1080/00207543.2021.2014591?needAccess=true (accessed Aug. 1, 2022).

[25] F. Mhenni *et al.,* "Heterogeneous Models Integration for Safety Critical Mechatronic Systems and Related Digital Twin Definition: Application to a Collaborative Workplace for Aircraft Assembly," *Applied Sciences*, vol. 12, no. 6, p. 2787, 2022. doi: 10.3390/app12062787. [Online]. Available: https://www.mdpi.com/2076-3417/12/6/2787

[26] H. Cai, W. Zhang, Z. Zhu, "Quality Management and Analysis of Aircraft Final Assembly Based on Digital Twin.", *2019 11th International Conference on Intelligent Human-Machine Systems and Cybernetics, IHMSC.*

[27] E. J. Tuegel, A. R. Ingraffea, T. G. Eason, S. M. Spottswood, "Reengineering Aircraft Structural Life Prediction Using a Digital Twin," *International Journal of Aerospace Engineering*, vol. 2011, pp. 1–14, 2011. doi: 10.1155/2011/154798. [Online]. Available: https://www.hindawi.com/journals/ijae/2011/154798/

[28] K. Henderson, A. Salado, "Value and benefits of model‐based systems engineering (MBSE): Evidence from the literature," *Syst Eng*, vol. 24, no. 1, pp. 51–66, 2021, doi: 10.1002/sys.21566.

[29] F. Gehlhoff *et al.,* "Challenges in Automated Commercial Aircraft Production," *IFAC-PapersOnLine*, vol. 55, no. 2, pp. 354–359, 2022, doi: 10.1016/j.ifacol.2022.04.219.

[30] M. Torres, "Parameters' monitoring and in-situ instrumentation for resin transfer moulding: A review," *Composites Part A: Applied Science and Manufacturing*, vol. 124, p. 105500, 2019, doi: 10.1016/j.compositesa.2019.105500.

[31] B. X. Chai *et al.,* "Simulation-based optimisation for injection configuration design of liquid composite moulding processes: A review," *Composites Part A: Applied Science and Manufacturing*, vol. 149, p. 106540, 2021, doi: 10.1016/j.compositesa.2021.106540.

[32] M. Seitz, T. Lucht, C. Keller, C. Ludwig, R. Strobelt, and P. Nyhuis, "Improving MRO order processing by means of advanced technological diagnostics and data mining approaches," *Procedia Manufacturing*, vol. 43, pp. 688–695, 2020, doi: 10.1016/j.promfg.2020.02.121.

Die Regulierung von Informationsinfrastruktur als Element der Verkehrslenkung unter besonderer Berücksichtigung von Verbünden autonomer Land-, Wasser und Luftfahrzeuge

Christian Worpenberg*, Prof. Dr. Margarete Schuler-Harms
Professur für Öffentliches Recht, ins. Öffentliches Wirtschafts- und Umweltrecht
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Hamburg, Deutschland
*christian.worpenberg@hsu-hh.de

***Kurzfassung* – Der Einsatz autonomer Fahrzeuge bedarf u.a. funktionsangemessener Verkehrsinformationsdienste. Diese Infrastrukturinnovation gilt es nicht nur technisch zu entwickeln, sondern auch mit Mitteln des Rechts sichere und kohärente Rahmenbedingungen zu schaffen. Ein besonderes Augenmerk des RIVA—Projekts liegt dabei auf den Schnittstellen zwischen unterschiedlichen Formen autonomer Fahrzeuge in multimodalen Verkehrsverbünden. Auch dort ist es angezeigt, Effektivitätsverluste und mögliche Störpotenziale im Verkehr zu vermeiden und auf diese Weise Verkehrsflüsse sicher zu machen und zu erleichtern. Dabei darf die suffiziente Beachtung datenschutz- und IT-sicherheitsrechtlicher Regelungen nicht außer Betracht bleiben.**

Stichworte – Autonome Fahrzeuge, Fahrzeugverbund, Informationsinfrastruktur, Verkehrslenkung, Verkehrssicherheit

I. Zur Einordnung: Verbundansatz des RIVA-Projektes und rechtswissenschaftliche Fragestellung

Schon im bemannten Verkehr werden für die Bewältigung verschiedener praktischer Aufgaben, z.B. im Rahmen von Gütertransporten oder Such- und Rettungseinsätzen, oft mehrere Verkehrsmittel eingesetzt und ihr Einsatz hierfür abgestimmt. Solche Fahrzeugverbünde dürften im autonomen Verkehr noch an Bedeutung gewinnen. Das Forschungsprojekt RIVA nimmt das Thema der Fahrzeugverbünde auf. Es widmet sich dabei sog. multimodalen Verbünden, in denen autonome Land-, Wasser- und Luftfahrzeuge miteinander kombiniert werden.

Im rechtswissenschaftlichen Teil des Projekts forschen wir zur staatlichen Regulierung in Bezug auf solche Verbünde. Die rechtlichen Grundlagen folgen bislang weitgehend sektorspezifischen Pfaden. Auch die rechtswissenschaftliche Forschung zur Mobilität erfolgt zumeist getrennt für Straße und Schiene, See und Luft. Einige einheitliche Regeln für multimodale Transporte im Güter- und Personenverkehr bilden nur eine kleine Ausnahme von diesem Grundsatz. Der Blick auf multimodale Verbünde kann diese sektorenbezogenen Perspektiven ergänzen, gerade zu einer Zeit, in der sich autonome Mobilität noch im Stadium der technischen Entwicklung befindet und auch die rechtlichen Grundlagen erst noch erarbeitet werden.

Aus rechtswissenschaftlicher Sicht wirft die Verbundperspektive besondere Fragen auf. Vieles spricht dafür, dass Verkehrsinformationsdienste unter Rücksicht (auch) auf solche Verbundstrukturen aufgebaut und betrieben werden sollten. Hieran schließt sich die Frage an, ob bereits das geltende Recht Verkehrsverbünde berücksichtigt und ob es Regulierungsstrategien aufweist, an die eine sektorenübergreifende Regulierung der Verkehrsinformationsdienste anschließen könnte. Der Klärung bedarf schließlich auch, welche rechtlichen Vorgaben unter Berücksichtigung von Verbünden für die Schaffung von Konvergenzen bestehen. Der vorliegende Beitrag erörtert diese Fragen am Beispiel der Regulierung der für solche Verbünde unerlässlichen Informationsinfrastruktur.

II. Informationsbedarfe in den Verkehrsbereichen und für den Verbund

Ein Fahrzeugverbund erfordert zunächst Daten über den Zustand der am Verbund beteiligten Fahrzeuge und über den Stand der auszuführenden Aufgabe sowie Positionsdaten. Darüber hinaus benötigen die beteiligten Fahrzeuge gut abgestimmte Informationen über Verkehrswege, die aktuelle Verkehrslage sowie Voraussetzungen und Grenzen der Benutzung bestimmter Wegstrecken. Auf den Bedarf an solchen Verkehrsinformationen gehen wir in diesem Beitrag ein. Der Sektor der Schiene bleibt dabei wegen seiner geringen Relevanz für die Verkehrsordnung außer Betracht.

Für den Einsatz autonomer Landfahrzeuge auf der Straße ergibt eine aktuelle Untersuchung, dass erst ab einem Anteil von deutlich über 50 % ebendieser Fahrzeuge am Gesamtverkehrsaufkommen eine Verbesserung des Verkehrsflusses bewirkt werde. Bis zum Erreichen dieses Grenzwertes sei mit erheblichen Verkehrsstörungen zu rechnen, die durch das Aufeinandertreffen von autonomen und nicht autonomen Fahrzeugen entstehen. Als Lösung schlägt die Untersuchung vor, mittels der Einrichtung besonderer

https://doi.org/10.24405/14563

Sensorik an den Straßen und des Einsatzes von Künstlicher Intelligenz (KI) den Verkehr digital abzubilden und über diese Informationen eine effizientere Routenplanung zu ermöglichen, welche die Verkehrssicherheit erhöhen und den Verkehrsfluss verbessern könne.[1]

Auch die (autonome) Luft- und Schifffahrt bedarf solcher Verkehrsinformationen. In der Binnenschifffahrt werden sie als sog. Nachrichten für die Binnenschifffahrt im Elektronischen Wasserstraßen- und Informationsservice (ELWIS) der Wasserstraßen- und Schifffahrtsverwaltung des Bundes veröffentlicht.[2] In der bemannten Luftfahrt verbreitet der Fluginformationsdienst Informationen z.B. über flugplatzbezogene Start- und Landeinformationen oder kurzfristig eintretende Beschränkungen des Luftverkehrs.[3] In der unbemannten Luftfahrt sollen statische und dynamische Daten der sog. U-Space-Lufträume über einen „gemeinsamen Informationsdienst“ verbreitet werden, um die Erbringung von sog. U-Space-Diensten für das Verkehrsmanagement von unbemannten Luftfahrzeugen zu ermöglichen.[4] Die Einrichtung solcher Lufträume hat die EU den Mitgliedstaaten ermöglicht, aber nicht vorgeschrieben.

Wenn autonome Fahrzeuge verbundhaft eingesetzt werden, können hieraus zusätzliche Informationsbedarfe entstehen und auch neue Kommunikationswege zu diskutieren sein. Denkbar wären etwa nötige Informationen über mögliche Rendezvous-Punkte. Darüber hinaus stellt sich auch die Frage, ob Informationen dezentral an alle Fahrzeuge gesendet oder zentral über einen Verbund-Leitstand kommuniziert werden sollten.

III. Vergleich der Regulierung von Verkehrsinformationen im geltenden Recht

Die auf Informationsinfrastrukturen bezogenen rechtlichen Vorgaben lassen sich daraufhin untersuchen, was die einzelnen Verkehrsbereiche voneinander lernen und wie sie sich gemeinsam weiterentwickeln können.

A. Regulierungszwecke

Ein Vergleich des bestehenden Rechts zeigt, dass in allen drei Verkehrsbereichen die vom jeweiligen Gesetzgeber bestimmten Zwecke der regulierten Verbreitung von Verkehrsinformationen nahezu deckungsgleich sind.

Für die Binnenschifffahrt ist geregelt, dass die Einführung und Nutzung der einschlägigen Informationsdienste die Sicherheit, Effizienz und Umweltfreundlichkeit der Binnenschifffahrt verbessern und die Verbindung mit anderen Verkehrsträgern erleichtern soll.[5]

In der unbemannten Luftfahrt wird dem gemeinsamen Informationsdienst im U-Space-Luftraum die Eigenschaft zugeschrieben, unverzichtbar für einen sicheren Betrieb unbemannter Luftfahrzeuge zu sein.[6] Gleiches gilt in der bemannten Luftfahrt für den Fluginformationsdienst[7], obschon dieser nicht gänzlich mit der besonderen Stellung des gemeinsamen Informationsdienstes als zentraler Datenplattform[8] für den unbemannten Luftverkehr vergleichbar ist[9].

Für den Straßenverkehr wird schon länger die Sammlung und Verbreitung von bestimmten Verkehrsinformationen als für die Sicherheit und Leichtigkeit des Straßenverkehrs dienlich angesehen.[10] Vergleichbare Zwecke werden für die Installation intelligenter Verkehrssysteme (IVS) im Straßenverkehr formuliert, die in jüngerer Zeit reguliert wurden. Auch IVS dienen der Erreichung einer effizienten, umweltverträglichen und sicheren Mobilität.[11] Dazu hat der EU-Gesetzgeber 2010 die Intelligente Verkehrssysteme Richtlinie (IVS-RL)[12] erlassen, welche der deutsche Gesetzgeber 2013 mit dem Intelligente Verkehrssysteme Gesetz (IVSG)[13] in nationales Recht umgesetzt hat. Ein wesentlicher Beweggrund für den Erlass der Richtlinie war, durch IVS eine sichere, koordinierte und kluge Nutzung der Verkehrsinfrastruktur zu ermöglichen und so den wachsenden Mobilitätsbedürfnissen Rechnung zu tragen.[14] In IVS werden Informations- und Kommunikationstechnologien im Straßenverkehr für Fahrzeuge und Nutzer, sowie beim Verkehrs- und Mobilitätsmanagement und für Schnittstellen zu anderen Verkehrsträgern eingesetzt.[15] Dazu sollen unter anderem EU-weite Echtzeit-Verkehrsinformationsdienste bereitgestellt werden.[16]

---

[1] Eine Zusammenfassung der Ergebnisse des Forschungsprojektes ACCorD gibt *Jahn*, Mehr Staus durch selbstfahrende Autos, in: Handelsblatt v. 16.4.2022; abrufbar unter: https://www.handelsblatt.com/technik/forschung-innovation/insight-innovation-mehr-staus-durch-selbstfahrende-autos-so-wollen-verkehrsforscher-das-problem-loesen/28254208.html (zuletzt abgerufen am 1.8.2022).

[2] Art. 4 Abs. 3 lit. d), Art. 5 Abs. 1 lit.c) der Richtlinie 2005/44/EG des Europäischen Parlaments und des Rates über harmonisierte Binnenschifffahrtsinformationsdienste (RIS) auf den Binnenwasserstraßen der Gemeinschaft v. 7.9.2005, ABl. L 255/152 v. 30.9.2005.

[3] § 27c Abs. 2 S. 1 Nr. 1 lit. c) LuftVG i.V.m. §§12 ff. FSDurchführungsV; *Risch*, in Grabherr/Reidt/Wysk, Luftverkehrsgesetz, Werkstand: EL 14, München August 2010, § 27c LuftVG Rn. 61.

[4] Art. 2 Nr. 4 i.V.m. Art. 5 der Durchführungsverordnung (EU) 2021/664 der Kommission über einen Rechtsrahmen für den U-Space v. 22.4.2021, ABl. L 139/161 v. 23.4.2022.

[5] Art. 1 Abs. 1 RL 2005/44 EG. S. auch Erwägungsgrund 1 RL 2005/44/EG.

[6] Erwägungsgrund 14 DVO (EU) 2021/664.

[7] § 12 FSDurchführungsV; *Risch*, in Grabherr/Reidt/Wysk, Luftverkehrsgesetz, Werkstand: EL 14, München August 2010, § 27c LuftVG Rn. 61.

[8] *Krumm*, EuZW 2020, 304.

[9] *Worpenberg/Valentiner/Johannsen/Goldberg*, NVwZ 2022, 1182 – NVwZ-Extra_10-2022, 9.

[10] § 44 Abs. 2 S. 2 StVO; § 2 Abs. 3 Nds. VILG.

[11] BT-Dr. 17/12371 v. 19.2.2013, S. 6.

[12] Richtlinie 2010/40/EU des Europäischen Parlaments und des Rates zum Rahmen für die Einführung intelligenter Verkehrssysteme im Straßenverkehr und für deren Schnittstellen zu anderen Verkehrsträgern v. 7.7.2010, ABl. L 207/1 v. 6.8.2010.

[13] Intelligente Verkehrssysteme Gesetz v. 11.6.2013 (BGBl. I S. 1553), zuletzt geändert durch Art. 1 des Gesetzes v. 17.7.2017 (BGBl. I S. 2640).

[14] Erwägungsgründe 1 und 3 RL 2010/40/EU.

[15] Art. 4 Nr. 1 RL 2010/40/EU.

[16] Art. 2 Abs. 1 Ziff. III IVS-RL.

Weitere Ansätze einer Regulierung von Mobilitätsdaten ergeben sich im Bereich der Personenbeförderung. Die Nutzung solcher Daten durch Länder und Kommunen – etwa zum Zwecke der Verkehrslenkung – kann nach Vorstellung des Gesetzgebers Effizienz und Klimafreundlichkeit des Verkehrs verbessern helfen. Sie dient damit dem in § 1a des Personenbeförderungsgesetzes (PBefG) verankerten Ziel der Umweltverträglichkeit von Personenbeförderung. Und nicht zuletzt, so die Gesetzesbegründung, schaffe die verkehrsträgerübergreifende Bereitstellung und Nutzbarmachung aktueller Mobilitätsdaten die Voraussetzungen, um datenbasierte, multimodale Mobilitätsdienste voranzutreiben.[17]

Im Koalitionsvertrag von 2021 wurde die Schaffung eines nationalen Mobilitätsdatengesetzes für die Straße vereinbart.[18] Mit der Regulierung der Verfügbarkeit von Mobilitätsdaten wird auch hier die Hoffnung verbunden, dass diese die Verkehrsplanung erleichtern, autonomes Fahren ermöglichen sowie die Verkehrssicherheit erhöhen werden.[19]

B. Ausgestaltung der Informationsinfrastruktur

Im Bereich der Binnenschifffahrt regelt die Europäische Kommission durch Verordnungen die technischen Spezifikationen für Informationsdienste wie Verteilungswege und die Nachrichteninfrastruktur.[20]

Für die technische Ausgestaltung des gemeinsamen Informationsdienstes nach der U-Space-VO fehlt es noch an detaillierten rechtlichen Anforderungen. Es steht zu erwarten, dass sie teils im Wege der Fortschreibung des Unionsrechts, teils mit der Anpassung des nationalen Rechts an das europäische Recht erlassen werden.

Im Straßenverkehr werden Verkehrsinformationen bisher nicht in gesetzlich standardisierter Form verarbeitet.[21] In einer Delegierten Verordnung der Europäischen Kommission von 2017 (DVO (EU) 2017/1926)[22] wird aber jeder Mitgliedstaat verpflichtet, einen nationalen Zugangspunkt[23] zu errichten, über welchen mindestens der Zugang zu statischen und historischen Verkehrsdaten verschiedener Verkehrsträger ermöglicht werden muss.[24] In Deutschland übernimmt diese Aufgabe bisher die Bundesanstalt für Straßenwesen mit dem „Mobilitäts Daten Marktplatz“[25], welcher bis Ende 2023 in der „Mobilithek“ aufgehen soll.[26] Für den Bereich der Personenbeförderung sind nach § 3a Abs. 1 PBefG Unternehmer und Vermittler von entgeltlichen Personenbeförderungsleistungen verpflichtet, statische und dynamische Daten sowie die entsprechenden Metadaten im Zusammenhang mit bestimmten Personenbeförderungen über den nationalen Zugangspunkt bereitzustellen.[27] Zu diesen Daten gehören etwa Fahrpläne und Routen, Abfahrts- und Ankunftszeiten sowie die tatsächliche oder prognostizierte Auslastung des Verkehrsmittels.[28] Näheres regelt die 2021 von der Bundesregierung erlassene Mobilitätsdatenverordnung.[29] Sie bestimmt die technischen Vorgaben an den Dateneingang und den Datenausgang bei der Bereitstellung dieser Daten, die zu verwendenden Datenformate und legt die Zusammenarbeit mit dem Nationalen Zugangspunkt fest.[30] Besondere Bedeutung kommt nach der Auffassung des Gesetzgebers dabei der Einhaltung hoher Standards zu, um Datenverlust oder Datenmanipulation vorzubeugen.[31] Für autonom fahrende Fahrzeuge entsprechend der SAE-Stufe 4[32] legt gleichlaufend die Autonome-Fahrzeuge-Genehmigungs-und-Betriebs-Verordnung (AFGBV)[33] fest, in welchen Datenkategorien und -formaten zu welchen Zeitpunkten eine Speicherung der in § 1g Abs. 1 StVG genannten Daten erfolgen darf.

[17] BT-Dr. 19/26175 v. 26.1.2021, S. 38.

[18] „Mehr Fortschritt wagen! – Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit“ Koalitionsvertrag 2021-2025, S. 41; vgl. a. Entschließungsantrag der FDP-Fraktion im Deutschen Bundestag „Umgang mit Fahrzeugdaten für Innovation, Sicherheit und Mobilität im 21. Jahrhundert“ v. 18.5.2021, BT-DR. 19/29755.

[19] Entschließungsantrag der FDP-Fraktion im Deutschen Bundestag „Umgang mit Fahrzeugdaten für Innovation, Sicherheit und Mobilität im 21. Jahrhundert“ v. 18.5.2021, BT-DR. 19/29755, S. 1.

[20] Siehe die auf Art. 5 RL 2005/44/EG i.d.F. der VO (EG) 219/2009 beruhenden VO (EG) 414/2007, VO (EG) 416/2007, geändert durch DVO (EU) 2018/2032 sowie die DVO (EU) 2019/1744.

[21] In Niedersachsen etwa werden teils von privaten Trägern geführte Verkehrsleitzentralen unterhalten, die mit der Sammlung, Aufbereitung und Verbreitung von Verkehrsinformationen beauftragt sind, § 2 Abs. 1, Abs. 2 S. 1 und 2 Nds. VILG. In NRW hingegen bestimmt ein Runderlass Zweck und Vorgehen eines Verkehrswarndienstes der Polizei, RdErl. d. Innenministeriums – 41.3. – 6220- v. 7.3.2003.

[22] Delegierte Verordnung (EU) 2017/1926 der Kommission zur Ergänzung der Richtlinie 2010/40/EU des Europäischen Parlaments und des Rates hinsichtlich der Bereitstellung EU-weiter multimodaler Reiseinformationsdienste v. 31.5.2017, ABl. L 272/1 v. 21.10.2017. Die Ermächtigung für diese Verordnung findet sich in Art. 6 Abs. 1, 7 Abs. 1 IVS-RL.

[23] Art. 2 Nr. 6 DelVO (EU) 2017/1926.

[24] Art. 3 Abs. 1 DelVO (EU) 2017/1926.

[25] BT-Dr. 19/26175 v. 26.1.2021, S. 38 f.

[26] Artikel des BMDV v. 1.7.2022, abrufbar unter: https://www.bmvi.de/SharedDocs/DE/Artikel/DG/mobilithek.html (zuletzt abgerufen am 8.8.2022).

[27] § 2 Nr. 11 IVSG.

[28] § 3a Abs. 1 Nr. 1 lit. a und b PBefG.

[29] Mobilitätsdatenverordnung v. 20.10.2021 (BGBl. I S. 4728), zuletzt geändert durch Art. 1 der Verordnung vom 1.7.2022 (BGBl. I S. 1039). Die erforderliche gesetzliche Ermächtigung findet sich in § 57 Abs. 1 Nr. 12 PBefG.

[30] §§ 3, 4 MDV; Verordnungsentwurf des BMDV v. 21.7.2021, BR-Dr. 615/21.

[31] BT-Dr. 19/26175 v. 26.1.2021, S. 39.

[32] SAE International, Levels of Driving Automation, SAE International Standard J3016, abrufbar unter: https://web.archive.org/web/20161120142825/http://www.sae.org/misc/pdfs/automated_driving.pdf (zuletzt abgerufen am 6.8.2022).

[33] § 15 Abs. 1 in Verbindung mit Anlage 2 der Verordnung zur Genehmigung und zum Betrieb von Kraftfahrzeugen mit autonomer Fahrfunktion in festgelegten Betriebsbereichen v. 24.6.2022 (BGBl. I S. 986).

IV. Regulierung von Informationsinfrastruktur (auch) aus der Verbundperspektive

Schon diese grobe Skizze der Regulierungszwecke und -ansätze lässt erkennen, dass sich die Regulierung der Informationsstruktur(en) für Straße, See und Luft aufeinander abstimmen lässt. In jedem Verkehrsbereich ist die Gewährleistung von Verkehrssicherheit ein zentrales Ziel. In allen Sektoren soll zudem die Informationsinfrastruktur die Effizienz der Verkehre und insbesondere deren reibungslosen Fluss mit dem Ziel der Leichtigkeit der Verkehre fördern.

Harmonisierend können auch die verfassungsrechtlichen Vorgaben wirken. Die Sorge für Verkehrssicherheit ist dem Staat verfassungsrechtlich aufgegeben.[34] Auch erfordert jeder Verkehrsbereich ein vom jeweiligen Sektor unabhängiges Niveau an Persönlichkeits- und Datenschutz.[35] Handlungsleitend können auch solche Grundrechte wirken, die freie Mobilität auch für multimodalen Verkehr gewährleisten und damit unter anderem die Ausübung weiterer Grundrechte erleichtern.[36] Soweit die Informationsbereitstellung die Effizienz des Verkehrs verbessert und insoweit auch dem Umweltschutz dient, lässt sich an den staatlichen Schutzauftrag aus Art. 20a GG denken.[37]

Sicherheitsrisiken, Effektivitätsverluste, Störpotenziale und Gefährdungen des Grundrechtsschutzes gilt es auch für den multimodalen Verbund zu vermeiden und so Verkehrsflüsse auch an den Übergängen zwischen den Verkehrsbereichen zu erleichtern. Autonome Fahrzeuge aller Verkehrsbereiche benötigen hierfür Daten im Hinblick auf die aktuelle Verkehrslage und Infrastrukturgegebenheiten anderer Verkehre und andersartiger Fahrzeuge. Daher empfiehlt es sich, für die Verkehrsinformationsdienste über die Sektoren hinweg mindestens gut kompatible, möglichst sogar einheitliche Datenformate zu wählen und die Anforderungen an die Datenqualität und deren Übertragungsweg sowie die Speicherung zu vereinheitlichen. Es dürfte sich auch empfehlen, gemeinsame Zugangspunkte für Informationen sowie gemeinsame Informationsdienste zu schaffen. Regelungen zum Datenschutz und zur IT-Sicherheit ließen sich harmonisieren, indem z.B. Speichervorschriften wie in Anlage 2 der AFGBV oder technische Sicherungssysteme wie die Etablierung einer technischen Aufsicht nach §§ 1d Abs. 3, 1e Abs. 2 StVG, 14 AFGBV verkehrsübergreifend entwickelt würden.

Der multimodale Fahrzeugverbund bildet dabei nur einen Anwendungsfall der Verbund-Perspektive. Ebenso gilt es, die Regulierungen für bemannten und unbemannten Verkehr – im jeweiligen Sektor sowie möglicherweise auch sektorenübergreifend – aufeinander abzustimmen. Der Bereich der Luft- und Binnenschifffahrt verdeutlicht außerdem, dass Verkehr nicht an Grenzen von Bundesländern oder Nationalstaaten Halt macht, sondern dass die Regulierung von Informationsermittlung, -aufbereitung und -verbreitung für Luft-, See- und selbst für den Straßenverkehr über geographische Grenzen hinaus zu denken ist. Vorbild für eine grenzüberschreitende Gestaltung von Verkehrsräumen und ihrer Regulierung könnte die Ausweisung von U-Space-Lufträumen nach Art. 3 Abs. 1 DVO (EU) 2021/664 sein, die nach Art. 3 Abs. 7 DVO (EU) 2021/664 ausdrücklich auch grenzüberschreitend erfolgen kann.

V. Ausblick auf das Projekt

Die Relevanz eines rechtswissenschaftlichen Blicks auf die Regulierung autonomer Verkehre, der solche Schnittstellen in Betracht zieht, ist damit verdeutlicht. Auch die Schritte der weiteren Arbeit deuten sich bereits an. Aus dem vorhandenen Regelungsbestand sind Elemente verbundbezogener Regulierung zu ermitteln. Gemeinsamkeiten und mögliche Nahtstellen für verbundhafte Regulierung sind festzuhalten und die fortlaufende Rechtsentwicklung aus dieser Perspektive zu beobachten. Die Arbeit hat zum Ziel, den insoweit bestehenden Regulierungsbedarf zu erheben und ggf. Vorschläge für eine die Verkehre integrierende Regulierung zu erarbeiten. Der Regulierung der Informationsinfrastruktur als unerlässlicher Voraussetzung für die Funktionsfähigkeit von Verkehrsverbünden kommt dabei zentrale Bedeutung zu.

Danksagung

Die Autoren bedanken sich für die Förderung bei dem dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt RIVA].

[34] Für das nationale Recht folgt dies aus einer Zusammenschau der Art. 1 Abs. 1, Art. 2 Abs. 2 S. 1, Art. 14 Abs. 1, Art. 20 Abs. 1 GG, vgl. *Vock*, NZV 1993, 59.

[35] Ihre grundrechtliche Ausprägung finden der Persönlichkeits- und Datenschutz insbesondere im Recht der informationellen Selbstbestimmung sowie der Gewährleistung von Vertraulichkeit und Integrität informationstechnischer Systeme jeweils als Teil des allgemeinen Persönlichkeitsrechts (Art. 2 Abs. 1 i.V.m. Art. 1 Abs. 1 GG); *Roßnagel*, Grundrechtsverwirklichung im vernetzten und automatisierten Straßenverkehr, in: Roßnagel/Hornung (Hrsg.), Grundrechtsschutz im Smart Car, Wiesbaden 2019, S. 17 (22).

[36] Art. 2 Abs. 1 und 2 S. 2, Art. 11 GG. Näheres dazu bei: *Roßnagel* (o. Fn. 35), S. 17 (19 f.).

[37] *Roßnagel* (o. Fn. 35), S. 17 (20); Erwägungsgrund 1 RL 2010/40/EU.

A Universal Approach to Command and Control Heterogeneous Autonomous Robots

Christoph Sieber*, Luis Miguel Vieira da Silva, Alexander Fay
Helmut-Schmidt-University
Hamburg, Germany
*christoph.sieber@hsu-hh.de

Tobias Brogt*, Gero Strobel
IT-Objects GmbH
Essen, Germany
*tobias.brogt@it-objects.de

Stephan Berkowitz*, Lukas Zembrot
Third Element Aviation GmbH
Bielefeld, Germany
*sb@3rd-element.com

***Abstract*—The usage of a team of heterogeneous, autonomous mobile robots makes it possible to execute a broad variety of scenarios more efficiently and effectively than single robots or a swarm of homogeneous robots ever could do. At the same time, the heterogeneity of these robots makes it difficult to command and control them and to manage their specific capabilities. In addition, it is crucial to test the robot team and its strategies before deploying them to the real world. Since neither a suitable development environment nor a suitable simulation environment are available, this paper presents an approach to enable heterogeneous robots to execute abstract missions on their own in a simulated environment. For this purpose, a sophisticated development and simulation environment has been developed and is demonstrated in this paper. Through this simulation environment, various control strategies can be tested to enable efficient use of a team of heterogeneous robots.**

***Index Terms*—autonomous robots, mobile robots, multi-robot systems, autonomy, simulation, drones**

I. Introduction

Mobile robots gain popularity due to their versatility and relevance in many situations. Robots are used in various sectors such as industry, businesses, and households to perform everyday activities and services. The demands on robots are constantly increasing as they have to accomplish more and more difficult scenarios [1]. But increasingly complex scenarios become more difficult to accomplish with single robots. In addition, responding to a dynamic environment is very challenging for a single robot [2]. Developing a robot that can quickly and safely meet all requirements to cover every possible scenario, is a costly and inefficient challenge [3]. Accordingly, complex scenarios should be accomplished jointly with a team of robots rather than with a single robot. This allows robots to complement each other and compensate for deficiencies of other robots. In addition, a team of collaborating and interacting robots can perform even faster and more effectively [4]. Another advantage is the robustness and reliability of a team of robots: if one robot in the team fails, the remaining robots might still be able to accomplish the scenario. Therefore, multi-robot systems (MRS) are considered [5]. For a team of robots, a distinction is made between a homogeneous and a heterogeneous robot team. A team of homogeneous robots consists of robots that have the same characteristics and capabilities such as a swarm of multiple identical Unmanned Aerial Vehicles (UAV). Different robots with different capabilities are considered in a team of heterogeneous robots [6]. The collaboration of several robots with different, complementary capabilities allows the accomplishment of very complex scenarios and is therefore being investigated in various research projects [2], [3]. However, mainly a heterogeneous robot team of one modality is considered. Thereby, the most frequently investigated modalities are land and air [7]. On the contrary, in the following, we will focus on a heterogeneous robot team of multiple modalities, such as land, air and water. The collaboration of the members of such a team allows to accomplish complex scenarios like search and rescue.

Due to this heterogeneity of a team and the specific capabilities of the individual robots associated with it, the number of possible solution strategies for the accomplishment of complex scenarios increases. This increases the effort to command and control a team of heterogeneous robots [5]. The interaction of different types of robots in an overall system in the context of simulations is still an unexplored area and corresponding simulation tools are not yet available. Therefore, this work is concerned with it.

This paper demonstrates an approach that reduces the effort required to command and control a team of heterogeneous robots. For this purpose, a multimodal applicable system architecture is presented as well as a method that fulfills the accomplishment of scenarios through structured partitioning. Section II gives a brief review of the state of the art of autonomous mobile robots and their development. In Section III the proposed system architecture of a single robot and the integration into a heterogeneous team is presented as well as the integration into the simulation is shown. Using this setup, Section IV demonstrates an application of the approach where a transport scenario is accomplished by a heterogeneous robot team consisting of an UAV and an Unmanned Ground Vehicle (UGV). Finally, a summary and an outlook on further research and development is given in Section V.

II. State of the Art

This section gives a brief overview of autonomous mobile robots. Essential terminologies and definitions are given and

https://doi.org/10.24405/14564

conclusively the common software for robot software development is presented.

A. Autonomous Mobile Robots

A robot is defined by ISO 8373 as a "programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation or positioning" [8]. Nevertheless, there are a variety of different interpretations of the definition of robots. Robots are often utilized when their environment is fully known and controlled. All their actions are known in advance and thus they do not need to act independently [9].

On the other hand, robots, and especially mobile robots, are considered to need to sense their environment and choose their actions accordingly. The mobile robot does not know the environment in advance, which is also not controllable, and thus does not have a fixed sequence of actions but must act and react in accordance with the environment. Such a robot operates according to certain rules corresponding to the sensed data [8]. Moreover, a mobile robot is a "robot able to travel under its own control" [8]. Finally, an autonomous mobile robot is a robot that acts without remote control [9]. Autonomy is considered a key capability of mobile robots, enabling increasingly complex missions, including teaming with other manned and unmanned entities to accomplish the overall scenario [10]. In the context of this article, a scenario refers to a setting of conditions and circumstances such as the currently available robots as well as an overall goal to be achieved. Missions, on the other hand, are derived from a scenario and consist of one or multiple tasks. Each mission requires one robot. The execution of each mission derived from the scenario provides a possible way to accomplish a scenario.

Thus, there are numerous scientific and legal definitions of autonomy, as e.g. in [9]. However, each of these definitions applies only to specific areas of law or selected technical applications. Accordingly, there is a lack of a unified and universally accepted definition applicable to a team of heterogeneous, multimodal robots. An attempt at a unified legal definition was made in [11]: "Autonomy is a state in which a robot system, once activated, is capable of autonomously performing some or all of the mission tasks, for a specified period of time or continuously, in specified areas or everywhere, while it must remain possible at all times for a technical supervisor to shut down the system to a low-risk, operable state in situations that cannot be foreseen by human judgement." (translated from [11]). The authors of this article endorse this definition, as it ensures human governance by setting the goal and operational framework, while it gives the robot a maximum of self-determination to operate.

B. Software Development Framework ROS2

The Robot Operating System (ROS) is an open-source middleware that is widely used for robotics applications and has become a de facto standard. The increasing demand for MRS has brought the awareness that ROS is not sufficient. ROS was designed to develop a single robot and does not provide a platform for MRS. Additionally, ROS is not real-time capable, which is necessary in complex applications of MRS. Other difficulties include vulnerability to failure due to lack of data encryption as well as lack of reliability [12]. These challenges have brought the development of ROS2. In this process, the successful concept is transferred into a new architecture. The big difference is the use of the Data Distribution Service (DDS) standard for communication, which enables data transfer between processes even on distributed heterogeneous platforms. There is a global data space that can be accessed by all applications.

In ROS2, nodes are used to represent independent computational processes. The use of nodes promotes modularity, reusability, and faster development. Communication between nodes can be done through topics or other methods such as services. Communication using topics follows a publish/subscribe model, where messages are passed through a clearly assignable topic. Nodes can subscribe to a topic by the name of that topic and receive the message when a node publishes on that topic [12]. Every node that publishes or subscribes to data is a participant that is allowed to write to and read from the data space. In contrast services represent a call/response model, where a service provides information only when it is called by a client [13].

At the same time, a node remains responsible for a specific, modular objective and can be treated and programmed in isolation [13]. Further, a node cannot be forced from an external source to behave in a certain way. The independence of the nodes and the use of DDS for communication allow MRS to be implemented while ensuring the autonomy of the individual robots and at the same time providing a capability to communicate and interact with the environment and especially other robots.

III. System Architecture & Integration

In the context of the deployment of a team of heterogeneous robots, a distinction can be made between three simulation stages of a single robot. On the one hand, there is a purely software-based simulation of all components, which is referred to as software in the loop (SiL) [14]. Furthermore, hardware components can be integrated into the simulation. This is referred to as hardware in the loop (HiL) [15]. The last step, which does not involve simulation in the strict sense, describes the deployment of a robot to the real world. This includes the installation of the necessary software on the real hardware components of the robot and the execution of these software modules, to control the robot in a real-world mission.

In addition to these stages of the deployment of a single robot, it is possible to form a team of robots from both simulated and real robots, for example based on a real robot and a simulated robot. This means that individual robots are used which are based on the different simulation stages described above. This makes it possible to evaluate different performance aspects at different levels reaching from the individual robot to the entire robot team. To enable such use cases for a broad range of heterogeneous robots in a simulation, a

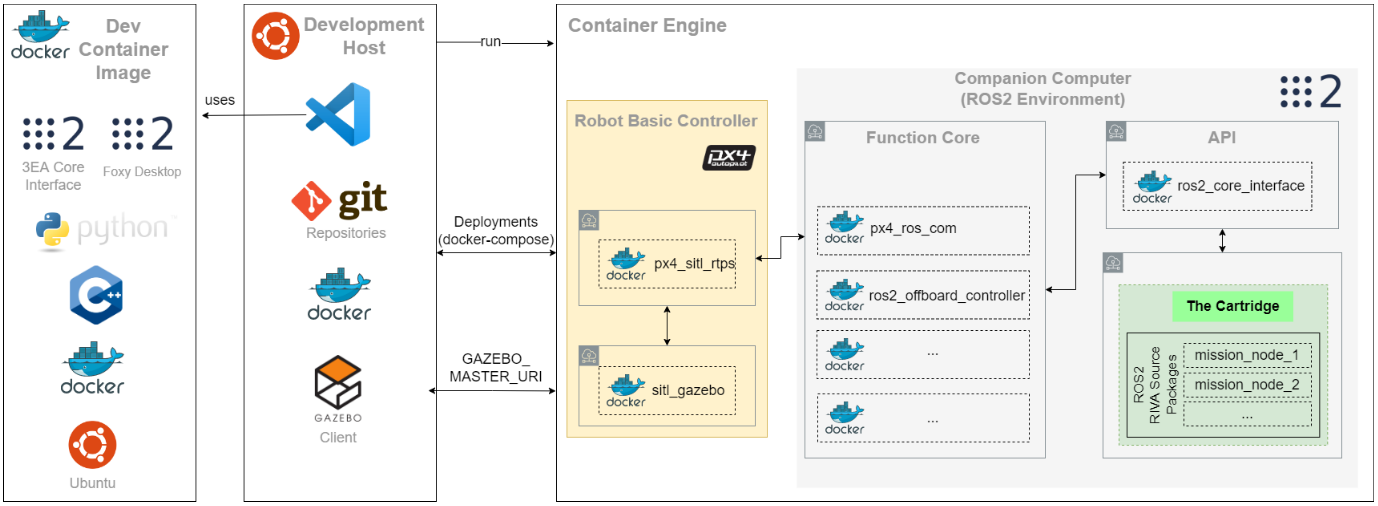


FIGURE 1. OVERVIEW DEVELOPMENT ENVIRONMENT.

powerful tool is required that enables the integration as well as the simulation of hardware components and real robots. In addition, a development environment integrated into the simulation is advantageous to quickly integrate new software modules into the existing infrastructure, for example, to be able to quickly evaluate adaptations to algorithms.

In order to fulfill the stated requirements, a simulator was developed. It is made up of various components and individual systems that make it possible to represent the various mentioned forms of simulation. The components and their interactions are shown in Fig. 1.

The initial aim was to make the installation and configuration of the simulator as simple as possible despite the large number of components. Container technology is used for this purpose. With the help of Docker[1], essential components are flexibly assembled and can be executed independently of the conditions on the host system. The integrated simulation tool runs on an Ubuntu based host system (Ubuntu 20.04 LTS) with a Docker installation. In addition the authors selected Gazebo[2] as the simulation environment because this tool is used extensively in research and practice, has many extensions, is under continuous development and has an active community of users as well as developers [16]. In addition, a separation of server and client is enabled, which reduces the total computing effort in a distributed system such as an MRS. The Gazebo client runs directly on the host system, while the Gazebo server is deployed using a Docker container. The client automatically connects to the server so that the simulation results calculated on the server can be easily displayed without requiring the server on the host system.

The Gazebo server is supplemented by a container that includes the Robot Basic Controller (RBC), which in the case of chosen UAV systems is represented by the px4 platform[3].

[1]https://docs.docker.com/
[2]https://gazebosim.org/home
[3]https//px4.io/

The RBC takes over all the necessary control mechanisms of a robot's sensors and actuators, such as controlling the different UAV rotors. The associated px4 autopilot-software is integrated with the Gazebo simulation to send commands to the robot and receive simulation data (e.g., sensor data and GPS positions).

The px4 uses a bridge module inside a further container, which maps messages between the RBC and the ROS2 Environment. ROS2 is chosen, because ROS is de facto the standard for the development of robots and for the development of a team of robots the further development ROS2 must be used. The ROS2 Environment contains on the one hand the robot specific nodes, the so-called Function Core. It controls the functional processes on the robot at a higher abstraction level than the RBC. The Function Core contains multiple ROS2 nodes, which are embedded in Docker containers. For each robot type, the RBC and the Function Core form a unit with basic functions that enable the fundamental operation of a robot. This unit also prevents aspects of unsafe behavior, e.g., planning robot trajectories outside defined safety zones. The number of basic functions is significantly dependent on the capabilities of a particular robot and is therefore finite or can only be changed by modifying the robot. It is therefore suitable to encapsulate them and to offer only one peripheral interface through which these basic functions can be executed as often as desired and in any order. Since this encapsulation is achieved by both hardware and software, reproducibility and modularity are also easily enabled.

On the other hand, the Cartridge is part of the ROS2 Environment. The Cartridge serves as an interface for the developers and allows individual testing and code variations, such as mission planning. The Cartridge is composed of nodes in containers that can be implemented in various approaches and programming languages like Python or C++. Several Cartridges can be deployed on a robot so that they can be tested alternatively or competitively. Here, for example, communication modules can be implemented to enable collaboration in a team of heterogeneous robots. All communication with the external world is done via the Cartridge. The Cartridge is connected to the robot specific nodes via the Core Interface. It provides an application programming interface for connecting the basic functions of the Function Core and RBC with creative functions, such as mission planning, which can be integrated here in the respective ROS2 nodes.

The number of creative functions depends only on the input of the developer and is therefore infinite. They can be individually extended or removed for the respective scenario, as well as for a broader range of use cases. Main advantage of the separation of creative functions from basic functions is the possibility for the developer to create and integrate software-modules to command and control the individual robot, without the need to address specific actuators or sensors, enabling the developers to target a broad range of heterogeneity.

In order to support the development of software in the Cartridge, Visual Studio Code[4] is used as the development environment (IDE). It integrates well with the components used, is open source and there are also many plug-ins for extending the IDE. In contrast to classic software development, the development environment does not run natively on the operating system of the host system, instead it is integrated into the system landscape of the simulation using container technology. The container contains all required dependencies, IDE extensions and mounts the source code repository, containing the development artifacts.

The container-based orchestration of the individual components of the simulator makes it possible to use the different simulation stages and their advantages. Gazebo represents the real world as a physics engine and simulates the behavior of the robots and provides corresponding sensor data, such as speeds or position data. The RBC simulates the control unit used for basic robot movement. A real robot for example can use a px4 autopilot-software, running on an associated hardware unit on the robot. The ROS2 Environment, running in containers on the host system, can be deployed in the same way on the real robot with the help of a companion computer. The two simulation stages of a single robot SiL and HiL both use Gazebo. For the SiL simulation, the RBC container and the ROS2 Environment containers are used. When running a HiL simulation, the RBC container is replaced with the real hardware used on the robot, which is then integrated with Gazebo and the ROS2 Environment. When forming a team of robots from both simulated and real robots, the above-mentioned procedures are combined in a flexible way. This allows for easy deployment and evaluation of mission execution.

IV. Application

In this chapter, the applicability of the presented approach is demonstrated by means of a simple transport scenario. This scenario simplifies a real-world problem, where a factory hall and a warehouse are separated from each other by difficult terrain. It is visualized in the simulation environment of Gazebo.

The goal of the scenario is to transport a box from a pick-up point to a drop-off point. Therefore, a team of heterogeneous robots is provided in a simulated setup. The team consists of one UAV and one UGV. As the robots are activated, they shall be capable of autonomously performing all mission tasks required to execute the transport. Due to environmental obstacles, the transport can neither be performed by the UAV nor by the UGV alone. The pick-up point is located on a flat surface on this side of a wall that the UGV cannot cross. The drop-off point is located on the other side of the wall, inside a building the UAV cannot enter. At the beginning, the UAV is located at the pick-up point and the UGV is near the drop-off point. Figure 2 shows this environment and the initial scenario setup.

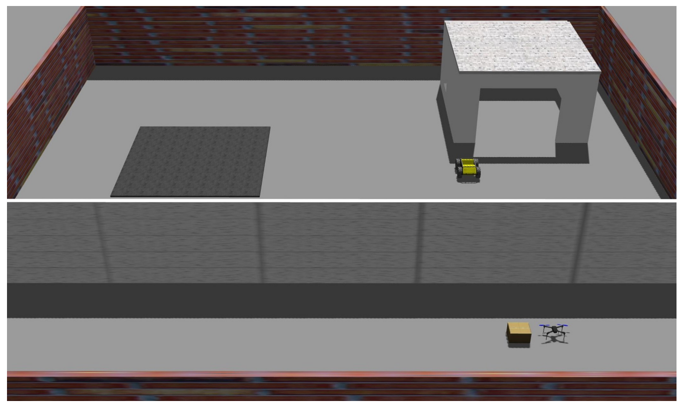


Figure 2. Initial Scenario Setup.

Consequently, the transport must be conducted sequentially with the use of both robots and by transferring the box at a specific handover point. Hence, the creative function of mission planning is used. This yields to one specific mission for the UAV and one specific mission for the UGV. These robot-specific missions are planned in an external mission-planning node and communicated to the individual robot. A mission is formulated abstractly, making it independent from basic functions. It therefore consists of abstract tasks, such as “move to a specific coordinate”, instead of “fly to a specific coordinate”.

After the UAV and the UGV each receive their specific missions, an internal mapping procedure is started. This mapping analyzes the mission by processing it task by task and identifies the basic functions required to execute the mission via the Core Interface.

The result is a sequence of basic functions called execution-list. Example: The UAV maps one abstract task “move to a specific coordinate” into two sequential basic functions “take-off” and “fly to a specific coordinate”. To ensure maximum autonomy in the execution of the mission, the exact flight trajectories are planned by the UAV.

As soon as the mapping is finished, the created execution-list is processed through the Core-Interface in a structured way.

[4]https://code.visualstudio.com/

In the given scenario, the UAV picks up the box, takes off, flies to the defined handover point, lands, drops the box, messages the UGV, takes off and flies back to the pick-up point, where it finally lands. The UGV starts driving to the handover point as soon as it receives the message from the UAV. There it picks up the box, drives to the drop-off point and unloads the box. FIGURE 3 shows the box lying at the handover point while the UAV flies back to the pick-up point and the UGV drives to the handover point.

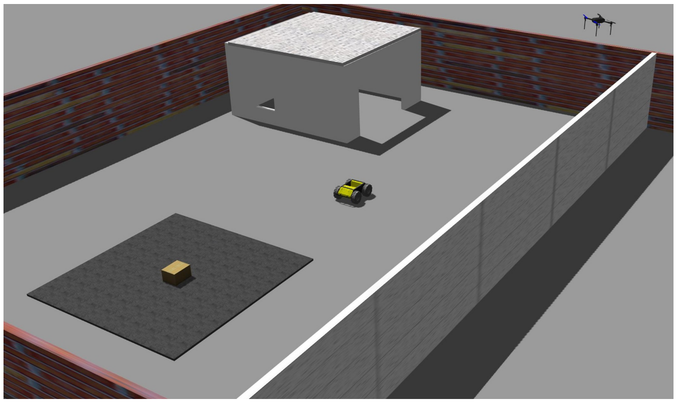


FIGURE 3. SCENARIO EXECUTION PROGRESS.

The scenario ends when the rover unloads the box. Both robots are now idle and available for following missions.

V. CONCLUSION AND OUTLOOK

In this article, an approach was presented that enables it to command missions to mobile robots, independent of their basic functions, and to let them execute those missions autonomously. For this purpose, an operative separation of basic functions and so-called creative functions is conducted in the system architecture of the robots. This architecture was presented and a simple transport scenario was used to demonstrate its functionality and effectiveness.

While the basic feasibility of the approach with respect to mission planning and execution has been demonstrated here, it also offers great potential for further research. An extension of the use cases to target a larger robot team of greater heterogeneity and modality is in progress. Additionally, other use cases are being considered due to the diverse applicability of a robot team. Since the approach allows the robots not only to be simulated, but also to be deployed in the real world, or to perform a hybrid simulation, these techniques are also under further investigation.

Mission planning is currently carried out by humans and only communicated automatically to the robots. With respect to the specific capabilities of the individual robots, it is intended to automate this planning process and only provide a common goal for the robot team. The presented separation of the basic functions and the creative functions represents a suitable prerequisite for this.

In addition, until now, the robots have carried out their missions sequentially in order to accomplish the given scenario. This poses challenges, especially in the case of unforeseen events. These can be overcome with interaction and collaboration between the individual robots and are empowered by the approach presented. The necessary replanning of missions is also part of the authors' research.

ACKNOWLEDGMENT

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project RIVA].

REFERENCES

[1] M. B. Alatise and G. P. Hancke, "A review on Challenges of Autonomous Mobile Robot and Sensor Fusion Methods," *IEEE Access*, vol. 8, pp. 39 830–39 846, 2020.

[2] Y. Rizk, M. Awad, and E. W. Tunstel, "Cooperative Heterogeneous Multi-Robot Systems," *ACM Computing Surveys*, vol. 52, no. 2, pp. 1–31, 2020.

[3] Y. Carreno, È. Pairet, Y. Petillot, and R. P. A. Petrick, "Task allocation strategy for heterogeneous robot teams in offshore missions," in *Proceedings of the 19th International Conference on Autonomous Agents and MultiAgent Systems*, 2020, pp. 222–230.

[4] Yifan Cai and Yang Simon X., "A survey on multi-robot systems," in *World Automation Congress 2012*, 2012, pp. 1–6.

[5] E. Tuci, M. H. M. Alkilabi, and O. Akanyeti, "Cooperative Object Transport in Multi-Robot Systems: A Review of the State-of-the-Art," *Frontiers in robotics and AI*, vol. 5, p. 59, 2018.

[6] H. Asama, "Trends of Distributed Autonomous Robotic Systems," in *Distributed autonomous robotic systems*, H. Asama, Ed. Tokyo: Springer, 1994, pp. 3–8.

[7] A. Schweim, M. Zager, M. Schweim, A. Fay, and J. Horn, "Unmanned Vehicles on the rise: A review on heterogeneous teams of cooperating robots," submitted for publication.

[8] ISO 8373:2021(E), "Robotics – Vocabulary," 2021.

[9] J. Hertzberg, K. Lingemann, and A. Nüchter, *Mobile Roboter: Eine Einführung aus Sicht der Informatik*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012.

[10] T. Petermann and R. Grünwald, "Stand und Perspektiven der militärischen Nutzung unbemannter Systeme," *Büro für Technikfolgenabschätzung beim Deutschen Bundestag, Arbeitsbericht*, vol. 144, 2011.

[11] C. Worpenberg, "Level 3, 4 oder 5? "Autonome" Fahrzeuge zu Land, Wasser und in der Luft - ein Plädoyer für eine verkehrsbereichsübergreifende Begriffseinführung von Automatisierungs- und Autonomiegraden," *InTeR Zeitschrift zum Innovations- und Technikrecht*, 2022.

[12] Y. Maruyama, S. Kato, and T. Azumi, "Exploring the performance of ROS2," in *Proceedings of the 13th International Conference on Embedded Software*, ser. ACM Digital Library. New York, NY: ACM, 2016, pp. 1–10.

[13] S. Macenski, T. Foote, B. Gerkey, C. Lalancette, and W. Woodall, "Robot Operating System 2: Design, architecture, and uses in the wild," *Science Robotics*, vol. 7, no. 66, p. eabm6074, 2022.

[14] S. Demers, P. Gopalakrishnan, and L. Kant, "A Generic Solution to Software-in-the-Loop," in *2007 IEEE Military Communications Conference*. Piscataway, NJ: IEEE Service Center, 2007, pp. 1–6.

[15] M. Bacic, "On hardware-in-the-loop simulation," in *2005 44th IEEE Conference on Decision and Control & European Control Conference*. Piscataway, NJ: IEEE Operations Center, 2005, pp. 3194–3198.

[16] N. Koenig and A. Howard, "Design and use paradigms for gazebo, an open-source multi-robot simulator," in *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, vol. 3. Piscataway, NJ: IEEE Operations Center, 2004, pp. 2149–2154.

Räumliche Auflösung des Schadenszustandes aus mechanischer und mathematischer Sicht

1st Wolfgang Weber
Professur für Statik und Dynamik
HELMUT-SCHMIDT-*Universität /*
Universität der Bundeswehr Hamburg
Hamburg, Deutschland
wolfgang.weber@hsu-hh.de

2nd Natalie Rauter
Professur für Mechanik
HELMUT-SCHMIDT-*Universität /*
Universität der Bundeswehr Hamburg
Hamburg, Deutschland
rautern@hsu-hh.de

3rd Rolf Lammering
Professur für Mechanik
HELMUT-SCHMIDT-*Universität /*
Universität der Bundeswehr Hamburg
Hamburg, Deutschland
rl@hsu-hh.de

4th Kathrin Welker
Professur für Mathematische Optimierung
Technische Universität Bergakademie Freiberg
Freiberg, Deutschland
Kathrin.Welker@math.tu-freiberg.de
bis 30.09.2022: Juniorprofessur für Mathematik im Bauingenieurwesen,
HELMUT-SCHMIDT-*Universität /*
Universität der Bundeswehr Hamburg

***Abstract*—Infrastrukturbauwerke des Straßenverkehrs sind in Mitteleuropa hohen und weiter steigenden Belastungen ausgesetzt. Für die Versorgung mit Gütern – auch zur Sicherstellung einer funktionierenden Volkswirtschaft – sowie zum Personentransport ist jedoch die Gewährleistung sowohl der Funktionalität als auch der Zuverlässigkeit dieser Infrastrukturbauwerke wie z. B. Brücken essenziell. Zur Abschätzung des Umfanges der für eine spezifische Brücke erforderlichen Instandhaltungsmaßnahmen ist zunächst eine Zustandserfassung erforderlich. Im geförderten Projekt soll hierfür eine kontinuierliche, sensorbasierte Zustandserfassung etabliert und dabei auf Erfahrungen aus anderen Ingenieurdisziplinen zurückgegriffen werden. Von besonderer Bedeutung sind hierbei Methoden der Mechanik, der Statik und Dynamik sowie der Mathematik, welche eine fundierte sensorgestützte Zustandsbewertung ermöglichen. Diese Methoden, offene Fragestellungen und mögliche Lösungswege werden in dem vorliegenden Beitrag diskutiert.**

***Index Terms*—SHM, geführte Ultraschallwellen, Schadensdetektion, Formoptimierung, variationelle Ungleichung**

I. EINLEITUNG

Für eine properierende Volkswirtschaft sind Stahlbetonbauwerke wie z. B. Brücken essenzielle Bestandteile der (Verkehrs-)Infrastruktur. Daher ist die Erhaltung deren Funktionalität und Zuverlässigkeit eine vorrangige Aufgabe. Die hierfür erforderliche Zustandserfassung der Brücken erfolgt derzeit jedoch lediglich durch zyklische Inspektionen nach DIN 1076, welche alle drei Jahre durchgeführt werden und in deren Ergebnis der jeweiligen Brücke eine Zustandsnote zugewiesen wird. Bedingt durch einerseits das zunehmende Bauwerksalter und andererseits den stark gestiegenen LKW-Verkehr ist ein zunehmende Verschlechterung dieser Zustandsnoten festzustellen. Somit hat sich in Deutschland ein immenser Bedarf an erforderlichen Instandhaltungsmaßnahmen aufgestaut. Hinzu kommen erforderliche Neubauten, welche jedoch nicht Gegenstand dieses Beitrages sind. Ein Beispiel einer Brücke, bei der Instandhaltungsmaßnahmen erforderlich sind, ist die Weserstrombrücke der BAB 2 nahe Bad Oeynhausen. Als Verbindung der Metropolregion Rhein-Ruhr mit der Bundeshauptstadt Berlin stellt die BAB 2 eine der wichtigsten Bundesautobahnen dar.

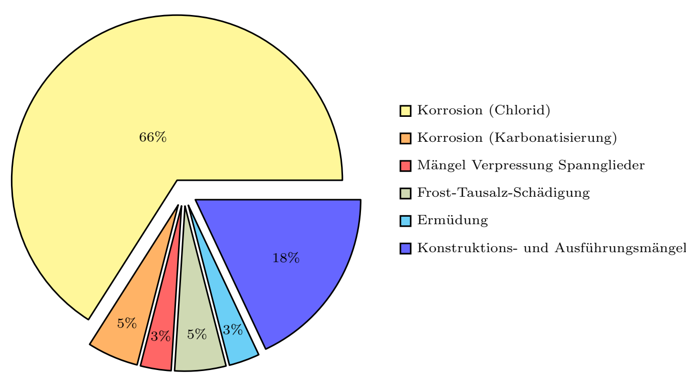


ABBILDUNG 1. TYPISCHE SCHADENSURSACHEN BEI BUNDESDEUTSCHEN AUTOBAHNEN, NACH [13].

Eine Inspektion der Brückenbauwerke aller drei Jahre ist einerseits aufwendig, andererseits stellt sie eine lediglich punktuelle Inspektion auf der Zeitachse dar. Es ist daher erstrebenswert, eine kontinuierliche und sensorbasierte Zustandserfassung (Structural Health Monitoring – SHM) zu etablieren, wie sie in Ingenieurdisziplinen wie dem Maschinenbau bereits üblich ist. Dies ist einer der Forschungsgegenstände des durch dtec.bw – Zentrum für Digitalisierungs-

https://doi.org/10.24405/14566

und Technologieforschung der Bundeswehr geförderten Forschungsprojektes “Digitalisierung von Infrastrukturbauwerken zur Bauwerksüberwachung: Structural Health Monitoring”. In dessen Teilprojekt 2 erfolgt der Transfer und die Weiterentwicklung von Methoden aus anderen Ingenieurdisziplinen, sodass dieses Teilprojekt stark von der Mathematik einerseits sowie der Mechanik bzw. Statik und Dynamik (im Folgenden abgekürzt: Mechanik) andererseits geprägt ist. Im Ergebnis des Forschungsprojektes soll die Restnutzungsdauer der alternden Stahlbetonbrücken besser ausgenutzt werden. Dies gelingt durch eine Reduktion der Ungewissheiten bei der Zuverlässigkeitsbewertung von Bauwerkszuständen.

Mit Blick auf die hierfür zu beantwortenden Fragestellungen aus dem Bereich der Mechanik und Mathematik ist festzustellen, dass sich Verfahren unter Einbeziehung von (Ultra-)Schall wie beispielsweise die Ausbreitung von (geführten) Ultraschallwellen oder Schallemmissionsanalysen als vorteilhaft für die Anwendung im Kontext des SHM erwiesen haben [23], [40]. Die weiterzuentwickelnden Methoden der Mechanik werden sowohl die Detektion als auch die Bewertung von typischen Schadensursachen gemäß ABBILDUNG 1 gestatten. Die zugrundeliegende Modellierung erfolgt nach einem schrittweisen Multiskalenansatz, wie er in ABBILDUNG 2 skizziert ist. Grundlage der mechanischen Methoden sind mathematische Verfahren wie beispielsweise die Formoptimierung (shape optimization) und inverse Algorithmen. Im Rahmen von SHM werden diese Verfahren zur Detektierung, Lokalisierung und Charakterisierung von Schäden genutzt und sind für die Bedürfnisse eines auf Infrastrukturbauwerke angepassten SHM ebenfalls weiterzuentwickeln. In der Kombination von Ultraschallmethoden mit Verfahren wie der Formoptimierung öffnet sich der Weg für die geplante Etablierung einer kontinuierlichen Bauwerksüberwachung für kritische (Verkehrs-)Infrastrukturbauwerke wie Brücken.

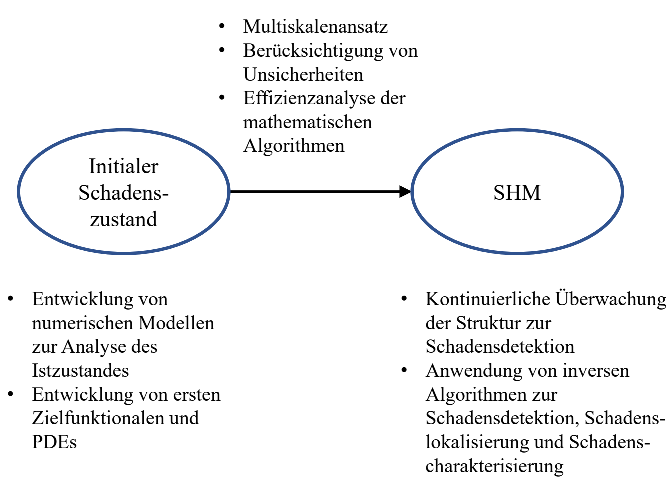


ABBILDUNG 2. ARBEITSSCHRITTE FÜR EIN MECHANISCH UND MATHEMATISCH MOTIVIERTES SHM.

Zur Beantwortung der sich daraus ergebenden Fragen ist der vorliegende Beitrag wie folgt gegliedert: in Abschnitt II erfolgt die Beschreibung des Vorgehens aus mechanischer Sicht, wobei zwischen zwei Betrachtungsebenen unterschieden wird. Der Abschnitt III dient der Darstellung der mathematischen Methoden, welche zur Erreichung der Forschungsziele verwendet bzw. entwickelt werden. Die Zusammenfassung folgt mit Abschnitt IV.

II. AUFLÖSUNG DES SCHADENSZUSTANDES AUS MECHANISCHER SICHT

Der derzeitige Stand des Wissens, welcher die Grundlage der Weiterentwicklung der erforderlichen mechanischen Methoden bildet, wird nachfolgend skizziert. Mit [28] liegt eine Übersichtsveröffentlichung zu derzeitigen Konzepten für die Bewertung von spannungsrisskorrosionsgefährdeten Brücken vor. Die Detektierung von Spanndrahtschädigungen sowie von Verpressfehlern ist intensiv in der DFG Forschungsgruppe DFG FOR 384 “Zerstörungsfreie Strukturbestimmung von Betonbauteilen mit akustischen und elektromagnetischen Echo-Verfahren” untersucht worden [11]. Allerdings konnte der Einfluss einiger wesentlicher Parameter und Randbedingungen auf die Ergebnisse der zerstörungsfreien Prüfung nicht abschließend geklärt werden. Insbesondere betrifft dies die Randbedingungen, die Dicke der Betondeckung, den Einfluss schlaffer Bewehrung und von Regionen mit hohen Bewehrungsgraden sowie der (geschichtete) Aufbau von Spannlitzen [12]. Ein Grund dafür, dass der Einfluss des (geschichteten) Aufbaues der Spannlitzen nicht geklärt werden konnte, liegt in dem Wellenlängenbereich des verwendeten Ultraschallsignales, welcher sich in der Größenordnung des Durchmessers des Spannstahles bewegt. Einige der vorgenannten Fragestellungen waren Gegenstand des DFG-Projektes “3D Ultraschallabbildungsverfahren für Betonbauteile” (DFG Projektnr. 69957132). Allerdings besteht noch immer Forschungsbedarf insbesondere bezüglich (i) der Ermittlung des Korrosionszustandes des Spannstahles und dessen Berücksichtigung im mechanischen Modell, (ii) des geschichteten Aufbaues der Interphase (d.h. eines Interface mit einer Dicke > 0), welche die Spannstahllitzen umgibt bzw. penetriert, sowie der Interphase, welche die Spannglieder umgibt und (iii) der Einfluss der Ungewissheiten in den Materialparametern einschl. deren räumlicher Verteilung, der Ungewissheiten in der Belastung sowie des Rauschens in den Messdaten; vgl. z. B. [13], [18]. Ansätze zur Beschreibung der Wellenausbreitung in vorgespannten Materialien mit Hohlräumen sind u. a. in [17], [36] vorgeschlagen. Jedoch bleibt festzuhalten, dass weder ein (geschichteter) Aufbau der elastischen Einschlüsse (d. h. der Bewehrungselemente) noch räumlich variierende Verbundeigenschaften untersucht wurden, sodass sich hier weiterer Forschungsbedarf ergibt. Zur Detektion eines plötzlichen Versagens von Verbundbereichen oder eines plötzlichen Risses einer Spannstahllitze wird die Schallemmissionsanalyse verwendet [19]. Nach derzeitigem Stand der Forschung kann eine verlässliche Lokalisierung eines solchen Schadens bisher (noch) nicht ausgeführt werden.

Auf der Grundlage dieser offenen Fragestellungen sind weitergehende Untersuchungen erforderlich, welche im Teilprojekt 2 des dtec.bw-Projektes “Digitalisierung von Infrastrukturbauwerken zur Bauwerksüberwachung: Structural Health Monitoring" ausgeführt werden. Die hierzu notwendigen Verfahren und Methoden im Bereich der mechanischen Fragestellungen lassen sich untergliedern in Ultraschallmethoden zur Schadensdetektion in heterogenen Materialien, die Multiskalenanalyse unter Berücksichtigung stochastischer Eingangsgrößen sowie die numerische Mechanik. Einige für das Projekt vielversprechende Forschungsansätze werden nachfolgend skizziert.

Für die Analyse der Ausbreitung von Ultraschallwellen unter Berücksichtigung der Wechselwirkung mit Schäden z. B. aus Ermüdungen infolge von zyklischen Belastungen sowie der ggf. resultierenden Delaminationen bietet sich die Verwendung des Ansatzes nach [20], [22] an. Die numerischen Simulationen haben ergeben, dass die Verwendung höherer harmonischer Moden und damit von nicht-linearen Wellen zur Detektion von Impakt- und Ermüdungsschäden vielversprechender ist als die bisher üblichen linearen Wellen [20]. Allerdings erfordert die Verwendung höherer harmonischer Moden im numerischen Modell die Implementierung nichtlinearen Materialverhaltens sowie finiter Verzerrungen, wie z. B. in [21] umgesetzt. In [23] konnte ergänzend gezeigt werden, dass eine neuartige hyperelastische Verzerrungsenergiedichtefunktion geeignet ist, die Ausbreitung nichtlinearer Wellen zu simulieren und somit die Detektion von Materialschädigungen zu verbessern.

Die Übertragung der Erkenntnisse auf der sogenannten Mikroskala auf die Makroskala erfolgt mittels einer Multiskalenmodellierung, welche die probabilistischen Eigenschaften auf der Mikrostruktur im numerischen Modell berücksichtigt [24]. Die numerische Modellbildung ist dabei durch Experimente validiert worden [25]. Die probabilistischen Eigenschaften auf der Mikrostruktur beinhalten beispielsweise die Größe, Orientierung und Verteilung von Bewehrungselementen in Laminaten. Mit Hilfe eines Monte-Carlo-Samplingprozesses werden künstliche (numerische) Mikrostrukturen erzeugt. Sobald eine ausreichend hohe Anzahl solcher Mikrostrukturen vorliegt, werden daraus sowohl die probabilistischen Eigenschaften als auch die räumliche Verteilung der Materialparameter abgeleitet. Die räumliche Verteilung dient darüber hinaus als Ausgangspunkt für die Erstellung GAUSSscher Zufallsfelder 2ter Ordnung. Diese erlauben die Einbeziehung räumlich verteilter Materialeigenschaften in das numerische Modell, ohne dabei die Mikrostruktur explizit abbilden zu müssen [25]. Eine Übertragung dieser Ansätze von Laminaten auf mineralisch gebundene Komposite ist jedoch noch offen und wird daher im Teilprojekt 2 des genannten dtec.bw-Forschungsprojektes umgesetzt.

Der Übergang von Laminaten zu mineralisch gebundenen Kompositen kann im mechanischen Modell für zeitharmonische bzw. transiente Belastungen gemäß [40], [41] erfolgen. Ein besonderer Schwerpunkt liegt dabei auf der Modellierung der Schadensentwicklung auf der sogenannten Mesoskala, z. B. für den dynamischen Auszug von Bewehrungselementen [42]. Ein mechanisches Modell, welches einen partiell vorgeschädigten Verbund zwischen einem starren Bewehrungselement und der einbettenden homogenen Matrix berücksichtigt, liegt mit [44] vor. Die auftretenden Dämpfungsphänomene können beispielsweise über [14] in das mechanische Modell integriert werden.

Variierende Materialparameter der Matrix, der Bewehrungselemente sowie der sich zwischen diesen ausbildenden Interphase werden auf der sogenannten Mikroskala abgebildet. Dabei wird die Ausbildung der Interphase stark durch chemische Prozesse während des Abbindevorganges beeinflusst. Um die sich daraus ergebenden Effekte auf die Wellenausbreitung adäquat zu berücksichtigen, wurde ein entsprechendes mechanisches Modell mit [43] vorgelegt. Ein Verfahren zur gezielten Verbesserung des Verbundverhaltens metallischer Bewehrungselemente ist in [3] dokumentiert. Insbesondere in Bauteilen mit hohen Bewehrungsgraden können elastische Wellen abgeschirmt werden, wie in [40] gezeigt wurde. Diese Effekte sind daher zu berücksichtigen, wenn aus den SHM-Untersuchungen auf konkrete Instandhaltungsmaßnahmen geschlossen werden soll. Die lokalen Variationen insbesondere in den Materialparametern der Matrix werden über eine Homogenisierung gemäß [46] erfasst. Dadurch wird ein Skalenübergang von der Mikro- auf die Mesoskale durchgeführt. Mit Blick auf die numerische Effizienz ist es vorteilhaft, vorab unbekannte Abhängigkeiten von Material- oder sonstigen Parametern zu berücksichtigen. Ein Ansatz zur automatisierten Detektion derartiger Abhängigkeiten unter Verwendung von Autoencodern liegt mit [27] vor. Neben den Ungewissheiten bei den Materialparametern sind jedoch auch die Belastungen und die Belastungsgeschichte des Ingenieurbauwerkes ungewiss. Um diese Ungewissheiten einzugrenzen und damit die Schlussfolgerungen aus der SHM zu präzisieren, ist ein erhöhter Aufwand erforderlich. Hier stellt sich die Frage, ob die infolge dieser Eingrenzung erhöhten monetären Kosten den zusätzlichen Aufwand rechtfertigen. Eine beispielhafte Kosteneffizienzanalyse wurde in [45] vorgeschlagen und ist auch auf die vorliegende Aufgabenstellung anwendbar. Die Materialparameter und damit auch das Strukturverhalten werden maßgeblich durch die Verarbeitungsweise der Materialien beeinflusst. Eine auf maschinellem Lernen basierende Untersuchung der Materialeigenschaften für verschiedene Verarbeitungen liegt mit [34] vor. Der bedeutende Anteil korrosionsbedingter Schäden bei bundesdeutschen Autobahnen ist aus ABBILDUNG 1 ersichtlich. Demnach besteht eine Hauptaufgabe des SHM in der Ermittlung bzw. der Ableitung des Korrosionszustandes. Ein entsprechendes Simulationsmodell liegt mit [35] vor.

III. AUFLÖSUNG DES SCHADENSZUSTANDES AUS MATHEMATISCHER SICHT

Zur Beantwortung der mathematischen Fragestellungen in der Auflösung des Schadenszustandes wird das Verfahren der Formoptimierung verwendet. Die Entwicklung von mathematischen Methoden, um bei einem bekannten Schadensort lokale Schadensaussagen treffen zu können und die Schadensausbreitung zu simulieren, ist ein Ziel des oben genannten Teilprojektes 2. Hierzu ist es geplant, Methoden der Formoptimierung mit Konzepten der RIEMANNschen Geometrie geschickt zu kombinieren. Ein Schaden wird hierbei als eine Form in einem RIEMANNschen Formenraum aufgefasst. Demzufolge benötigt man zunächst einen Raum, der alle möglichen zulässigen Formen enthält. Ein Punkt aus diesem Raum der Formen beschreibt dann genau eine mögliche Form (siehe ABBILDUNG 3 zur Veranschaulichung). Definiert man nun eine geeignete RIEMANNsche Metrik auf dem Raum der Formen, so ist es möglich, den Raum und dessen Elemente, die Formen, zu untersuchen. RIEMANNsche Metriken führen unter anderem zu Metriken und Geodätischen. Mit Hilfe der Metriken kann man Aussagen darüber treffen, wie ähnlich sich zwei Formen sind und mit Hilfe der Geodätischen, wie eine Form aus der anderen hervorgeht. Gerade die Geodätische werden ein wichtiges Hilfsmittel zur Simulation der Schadensausbreitung sein. Kennt man zum Beispiel die Geodätische zwischen zwei Punkten aus dem Raum der Formen, so erhält man durch Fortsetzung der Geodätischen weitere Punkte. Diese Punkte beschreiben dann, wie sich die Form wie beispielsweise ein Riss im Verlauf der Zeit weiter verändern wird.

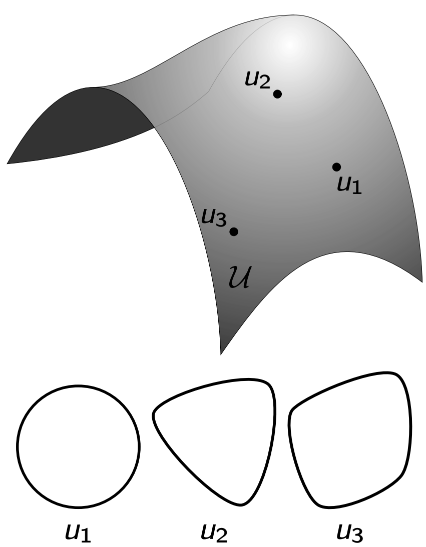


ABBILDUNG 3. ILLUSTRATION EINES MÖGLICHEN ABSTRAKTEN FORMENRAUMS $\mathcal{U}$, DESSEN ELEMENTE (VERANSCHAULICHT DURCH DIE PUNKTE u_1, u_2, u_3 AUF $\mathcal{U}$) BEISPIELE FÜR FORMEN SIND, DIE IN EINEM OPTIMIERUNGSPROZESS ALS OPTIMALLÖSUNGEN ZULÄSSIG WÄREN.

Im Allgemeinen zeichnet sich die Formoptimierung durch eine Vielzahl an praktischen Anwendungsfeldern aus. Exemplarisch seien Formoptimierungen in der Aerodynamik [30], der Akustik [39] sowie Optimierungen von Grenzflächen in Transmissionsproblemen [4], [15], [16] genannt. Dabei werden vor allem in vielen praktischen Anwendungen Formen durch endlich viele Parameter charakterisiert. Insbesondere mit Blick auf den im SHM-Projekt vorliegenden industriellen Kontext ist festzustellen, dass häufig eine *à priori* Parametrisierung der Formen stattfindet. Einerseits ermöglicht dies die Anwendung von Standardoptimierungsansätzen, andererseits wird der Raum der erreichbaren Formen unnötig begrenzt, was zur Folge haben kann, dass die optimale Form ausgeschlossen wird. Aus diesem Grunde wird im vorliegenden Projekt diese Restriktion fallengelassen und stattdessen eine Lösung im RIEMANNschen Formenraum angestrebt. In [47] wird ein effizientes Vorgehen zur Formoptimierung in Formenräumen unter Verwendung von RIEMANNschen Mannigfaltigkeiten entwickelt.

Da ein deterministischer Optimierungsansatz außer Acht lässt, dass im SHM-Projekt stochastische und ungewisse Variationen der Parameter auftreten, werden im Teilprojekt 2 ebenfalls Aspekte der Robustheit adressiert. So sind beispielsweise die Betriebsbedingungen nicht exakt bekannt, d. h. die Variation der makroskopischen Parameter ist ungewiss. Die exakte Form ist infolge der Herstellungstoleranzen zunächst nicht bekannt. Darüber hinaus verändert sich die zu optimierende Form durch mechanische Belastungen während des Betriebes. Ohne eine adäquate Berücksichtung dieser Abweichungen von den angenommenen Randbedingungen kann ein Ergebnis der (Form-)Optimierung nutzlos sein. Daher stellt die Einbeziehung dieser Ungewissheiten eine bedeutende Forschungsfrage dar. Robuste Optimierung hat sich zu einem umfangreichen Forschungsgebiet entwickelt, wobei Robustheitskonzepte unabhängig voneinander in verschiedenen wissenschaftlichen Disziplinen entwickelt wurden, vgl. z. B. [1], [2], [8], [26], [38]. Deutliche Verbesserungen von robusten gradientenbasierten Formoptimierungen sind in [29] dokumentiert. Erste Ergebnisse einer stochastischen Näherung optimaler Formen im Formenraum liegen mit [5]–[7] vor. Einige für das Projekt vielversprechende Forschungsansätze werden nachfolgend skizziert.

Formoptimierungen mit Beschränkungen, welche sich durch partielle Differentialgleichungen (PDEs) und variationelle Ungleichungen (VIs) beschreiben lassen, können mit den Ansätzen aus z. B. [10], [31], [32], [47] gelöst werden. Neben Formoptimierungen im klassischen Sinne ist wie oben beschrieben auch eine Lösung im Rahmen der Differentialgeometrie mit Blick auf RIEMANNsche Objekte vielversprechend, entsprechende Ansätze liegen mit [9], [47], [48] vor. Für Diskretisierungen im vorliegenden Forschungsprojekt wird die Finite-Elemente-Methode (FE-Methode) verwendet, weshalb die in [33] vorgeschlagene STEKLOV-POINCARÉ-Metrik für die Verwendung der FE-Methode sehr aussichtsreich ist. Unter gewissen Voraussetzungen führt diese Metrik auf Formen der Klasse $H^{1/2}$, welche als erstes in [48] entwickelt wurden und in diesem Projekt genutzt werden sollen. Die Kombination des Raumes der $H^{1/2}$-Formen und der STEKLOV-POINCARÉ-Metrik ist eine wichtige Weiterentwicklung, welche die Anwendung effizienter FE-Löser ermöglicht, siehe [37], worin die Interaktion von Mehrgitterverfahren und Formoptimierung in geeigneten Formenräumen untersucht wird. Sowohl die Mehrgitterverfahren als auch Quasi-NEWTON-Verfahren sind notwendig, um eine vernetzungsunabhängige Konvergenz und damit skalierbare Algorithmen – z. B. zur Verwendung in Supercomputern – zu erhalten. Dies öffnet den Weg zur realitätsnahen Untersuchung auch von 3D-Problemen.

Um Ungewissheiten in den Messdaten zu berücksichtigen, ist der Modellierungsprozess um stochastische Aspekte zu erweitern. Hierbei kann auf die Verfahren [5]–[7] zurückgegriffen und diese erweitert werden. Mit [6] liegt ein Beitrag einer stochastischen Näherung in Formenräumen vor. Die numerischen Apsekte dieses Ansatzes sind z. B. in [5], [7] untersucht. Eine Erweiterung des Verfahrens, welche die Behandlung von mehreren Formen ermöglicht, ist in [7] beschrieben. Grundlage dieses Verfahrens ist eine neuartige Formulierung der Ableitung von Formen. Mit Blick auf das vorliegende Projekt eröffnet sich damit die Möglichkeit, mehr als einen Schaden zu detektieren.

IV. Zusammenfassung

Die Etablierung einer kontinuierlichen Zustandsüberwachung von Infrastrukturbauwerken erfordert umfangreiche Forschungsarbeiten auf dem Gebiet der Mathematik, der Mechanik sowie der Statik und Dynamik. Diese Weiterentwicklungen betreffen u. a. die Sensoranzahl und -platzierung, die adäquate Beschreibung der verwendeten Kompositmaterialien sowohl auf der Mikroebene als auch – unter Verwendung eines Multiskalenansatzes – auf der Makroebene sowie Weiterentwicklungen mathematischer Methoden wie der Formoptimierung, um mehr als einen Schaden detektieren und lokalisieren zu können und Schadensaussagen zu formulieren. Ein besonderer Schwerpunkt wird auf die Berücksichtigung von Vorschädigungen sowie von Ungewissheiten gelegt. Nachdem im Forschungsprojekt somit ein physikalisch und mathematisch fundiertes Verfahren zur Detektion und Lokalisierung von Schäden entwickelt worden sein wird, ist in einem nächsten Schritt die Bewertung der Schäden mit Blick auf die zu erwartende Restnutzungsdauer von Interesse.

Danksagung

Dieser Beitrag ist gefördert durch dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr, Projekt “Digitalisierung von Infrastrukturbauwerken zur Bauwerksüberwachung: Structural Health Monitoring”.

Literaturverzeichnis

[1] A. Ben-Tal, L. El Ghaoui & A. Nemirovskri, Robust Optimization. Princeton University Press, 2009.

[2] S. Conti, H. Held, M. Pach, M. Rumpf & R. Schultz, “Risk Averse Shape Optimization”, SIAM Journal on Control and Optimization, vol. 49(3), pp. 927–947, 2011, doi: 10.1137/090754315 .

[3] B. Daneshian, F. Gärtner, H. Assadi, D. Höche, W. Weber & T. Klassen, “Size Effects of Brittle Particles in Aerosol Deposition – Molecular Dynamics Simulation”, Journal of Thermal Spray Technology, vol. 30(3), pp. 503–522, 2021, doi: 10.1007/s11666-020-01149-9 .

[4] P. Gangl, A. Laurain, H. Meftahi & K. Sturm, “Shape optimization of an electric motor subject to nonlinear magnetostatics”, SIAM Journal on Scientific Computing, vol. 37(6), pp. B1002–B1025, 2015.

[5] C. Geiersbach, E. Loayza & K. Welker, “Computational Aspects for Interface Identification Problems with Stochastic Modelling”, ArXiv Preprint 1902.01160, 2020, https://arxiv.org/abs/1902.01160.

[6] C. Geiersbach, E. Loayza & K. Welker, “Stochastic approximation for optimization in shape spaces”, SIAM Journal on Optimization, vol. 31(1), pp. 348–376, 2021.

[7] C. Geiersbach, E. Loayza & K. Welker, “PDE-constrained shape optimization: towards product shape spaces and stochastic models” in Handbook of Mathematical Models and Algorithms in Computer Vision and Imaging, K. Chen, C.-B. Schönlieb, X.-C. Tai& L. Younes (Eds.), Springer, 2021 (*eingereicht*), https://arxiv.org/abs/1902.01160.

[8] L. El Ghaoui, M. Oks & F. Oustry, “Worst-Case Value-At-Risk and Robust Portfolio Optimization: A Conic Programming Approach”, Operations Research, vol. 51(4), pp. 543–556, 2003.

[9] N. Goldammer & K. Welker, “Towards optimization techniques on diffeological spaces by generalizing Riemannian concepts”, (*eingereicht bei bei Applied Mathematics and Optimization*), 2021, https://doi.org/10.48550/arXiv.2009.04262 .

[10] D. Luft, V. Schulz & K. Welker, “Efficient techniques for shape optimization with variational inequalities using adjoints”, SIAM Journal on Optimization, vol. 30(3), pp. 1922–1953, 2020.

[11] K. Mayer, B. Milman, M. Krause & F. Mielentz, “Methode zum Nachweis von Verpressfehlern in Spannbeton durch Phasenauswertung bei Ultraschallecho-Verfahren”, ZfP-Zeitung, vol. 112(12), pp. 37–40, 2008.

[12] B. Milman, M. Krause, F. Mielentz & K. Mayer, “Ultraschallecho-Verfahren für Spannbeton: Signifikanter Nachweis von Verpressfehlern mit Phasenauswertung”, pp. p11, 2008 [Fachtagung Bauwerksdiagnose 2008].

[13] S. Müller, “Erarbeitung von Modellen zur Bestimmung der Schadensumfangsentwicklung an Brücken”, Dissertation, BASt-Bericht B 111, 2014.

[14] P.C. Müller & W.E. Weber, “Modal analysis and insights into damping phenomena of a special vibration chai”, Archive of Applied Mechanics, vol. 91(1), pp. 2179–2187, 2021, doi: 10.1007/s00419-020-01876-z .

[15] A. Nägel, V. Schulz, M. Siebenborn & G. Wittum, “Scalable shape optimization methods for structured inverse modeling in 3D diffusive processes”, Computing and Visualization in Science, vol. 17, pp. 79–88, 2015, doi: 10.1007/s00791-015-0248-9.

[16] A. Paganini, “Approximative shape gradients for interface problems”, Seminar for Applied Mathematics, ETH Zürich, 2014-12.

[17] W.J. Parnell & I.D. Abrahams, “Antiplane Wave Scattering from a Cylindrical Void in a Pre-Stressed Incompressible Neo-Hookean Material”, Communications in Computational Physics, vol. 11(2), pp. 367–382, 2012.

[18] J.S. Popovics, J.R. Roesler, J. Bittner, A.N. Amirkhanian, A.S. Brand, P. Gupta & K. Flowers, “Ultrasonic imaging for concrete infrastructure condition assessment and quality assurance”, Illinois Center for Transportation Series, vol. 17(011), 2017.

[19] F. Pottmeyer, O. Schlegel, K.A. Weidenmann & M. Merzkirch, “Investigation of the damage evolution of metal inserts embedded in carbon fiber reinforced plastic by means of computed tomography and acoustic emission”, Materials Science & Engineering Technology, vol. 49(10), pp. 1245–1262, 2018, doi: 10.1002/mawe.201800002.

[20] N. Rauter & R. Lammering, “Impact Damage Detection in Composite Structures Considering Nonlinear Lamb Wave Propagation”, Mechanics of Advanced Materials and Structures, vol. 22(1-2), pp. 44–51, 2015, doi: 10.1080/15376494.2014.907950.

[21] N. Rauter & R. Lammering, “Numerical simulation of elastic wave propagation in isotropic media considering material and geometrical nonlinearities”, Smart Materials and Structures, vol. 4(4), pp. 045027, 2015, doi: 10.1088/0964-1726/24/4/045027.

[22] N. Rauter, R. Lammering & T. Kühnrich, “On the detection of fatigue damage in composites by use of second harmonic guided waves”, Composite Structures, vol. 152, pp. 247–258, 2016, doi: 10.1016/j.compstruct.2016.05.049.

[23] N. Rauter & R. Lammering, “A constitutive model for the analysis of second harmonic Lamb waves in unidirectional composites”, International Journal of Solids and Structures, vol. 135, pp. 184–196, 2018, doi: 10.1016/j.ijsolstr.2017.11.019.

[24] N. Rauter & R. Lammering, “Correlation structure in the elasticity tensor for short fiber-reinforced composites”, Probabilistic Engineering Mechanics, vol. 62, pp. e103100, 2020, doi: 10.1016/j.probengmech.2020.103100.

[25] N. Rauter & R. Lammering, “Experimental Characterization of Short Fiber-Reinforced Composites on the Mesoscale by Indentation Tests”, Applied Composite Materials, vol. 28, pp. 1747–1765, 2021, doi: 10.1007/s10443-021-09937-4.

[26] A. Ruszczyński & A. Shapiro, "Stochastic programming model", Handbooks in operations research and management science, vol. 10, pp. 1–64, 2003.

[27] U. Reuter, A. Jayaram, M. Rezkalla & W. Weber, "A novel approach for automatic detection of linear and nonlinear dependencies between data by means of autoencoders", Neurocomputing, vol. 471, pp. 285–295, 2022, doi: 10.1016/j.neucom.2021.10.079.

[28] G. Schacht, M. Käding, G. Bolle & S. Marx, "Konzepte für die Bewertung von Brücken mit Spannungsrisskorrosionsgefahr", Beton- und Stahlbetonbau, vol. 111(2), pp. 85–94, 2019.

[29] C. Schillings & V. Schulz, "On the influence of robustness measures on shape optimization with stochastic uncertainties", Optimization and Engineering, vol. 16(2), pp. 347–386, 2015, doi: 10.1007/s11081-014-9251-0.

[30] S. Schmidt, C. Ilic, V.H. Schulz, and N. Gauger, "Three dimensional large scale aerodynamic shape optimization based on the shape calculus," AIAA Journal, 51(11):2615–2627, 2013.

[31] V. Schulz, M. Siebenborn & K. Welker, "Structured inverse modeling in parabolic diffusion problems", SIAM Journal on Control and Optimization, vol. 53(6), pp. 3319–3338, 2015.

[32] V. Schulz, M. Siebenborn & K. Welker, "Towards a Lagrange-Newton approach for PDE constrained shape optimization" in: New Trends in Shape Optimization, A. Pratelli & G. Leugering (Eds.), Springer, 2015, pp. 229–249.

[33] V. Schulz, M. Siebenborn & K. Welker, "Efficient PDE Constrained Shape Optimization Based on Steklov-Poincaré-Type Metrics", SIAM Journal on Optimization, vol. 26(4), pp. 2800–2819, 2016, doi: 10.1007/s11081-014-9251-0.

[34] M. Shariati, W. E. Weber, J. Bohlen, G. Kurz, D. Letzig & D. Höche, "Parallel simulation of the POISSON-NERNST-PLANCK corrosion model with an algebraic flux correction method", Materials Science and Engineering: A, vol. 794, pp. 139846, 2020, doi: 10.1016/j.msea.2020.139846.

[35] M. Shariati, W. E. Weber & D. Höche, "Parallel simulation of the POISSON-NERNST-PLANCK corrosion model with an algebraic flux correction method", Finite Elements in Analysis and Design, vol. 206, pp. 103734, 2022, doi: 10.1016/j.finel.2022.103734.

[36] T. Shearer, W. J. Parnell & I. D. Abrahams, "Antiplane wave scattering from a cylindrical cavity in pre-stressed nonlinear elastic media", Proceedings of the Royal Society A, vol. 471(2182), pp. 20150450, 2015.

[37] M. Siebenborn & K. Welker, "Algorithmic aspects of multigrid methods for optimization in shape spaces", SIAM Journal on Scientific Computing, vol. 39(6), pp. B1156–B1177, 2017.

[38] A. Soyster, "Convex Programming with Set-Inclusive Constraints and Applications to Inexact Linear Programming", Operations Research, vol. 21(5), pp. 1154–1157, 1973.

[39] R. Udawalpola and M. Berggren, "Optimization of an acoustic horn with respect to efficiency and directivity," International Journal for Numerical Methods in Engineering, Wiley Online Library, 73(11):1571–1606, 2007.

[40] W. Weber & M. Curbach, "Wellenausbreitung in bewehrten Feinbetonpaneelen", Beton- und Stahlbetonbau, vol. 108(8), pp. 562–569, 2013, doi: 10.1002/best.201200068.

[41] W. Weber & B. W. Zastrau, "Analytical description of FRC subjected to transient loads", Journal of Theoretical and Applied Mechanics, vol. 51(1), pp. 183–194, 2013.

[42] W. Weber, Y. Fangye, D. Balzani & B. Zastrau, "Analytical and Numerical Modelling of a Sub- and Supersonic Moving Load Front Along a Rod's Skin" in: Advanced Methods of Continuum Mechanics for Materials and Structures, K. Naumenko and M. Aßmus (Eds.), Singapore: Springer Singapore, 2016, pp. 469–489, doi: 10.1007/978-981-10-0959-4_26.

[43] W. Weber & V. Mechtcherine, "Modeling the dynamic properties of fibre-reinforced concrete with different coating technologies of multifilament yarns", Cement and Concrete Composites, vol. 73, pp. 257–266, 2016, doi: 10.1016/j.cemconcomp.2016.07.017.

[44] W. Weber & G. Manolis, "Dynamic behaviour of rigid inclusions with circumferential damage embedded in an elastic matrix", Archive of Applied Mechanics, vol. 87(7), pp. 1095–1104, 2017, doi: 10.1007/s00419-017-1238-9.

[45] W. Weber & U. Reuter, "Fuzzy modeling of wave-shielding under consideration of cost-effectiveness for an efficient reduction of uncertainty", Advances in Engineering Softwares, vol. 109, pp. 53–61, 2017, doi: 10.1016/j.advengsoft.2017.03.005.

[46] E. Zimmermann & W. Weber, "Influence of the correlation lengths on the continuous mode conversion", PAMM, vol. 20(1), pp. 202000245, 2020, doi: 10.1002/pamm.202000245.

[47] K. Welker, "Efficient PDE constrained shape optimization in shape spaces", Dissertation, Universität Trier, 2016, https://ubt.opus.hbz-nrw.de/frontdoor/index/index/docId/740.

[48] K. Welker, "Suitable spaces for shape optimization", Applied Mathematics and Optimization, vol. 84(1), pp. 869–902, 2021, doi: 10.1007/s00245-021-09788-2.

Covariate-adjusted Association of Sensor Outputs for Structural Health Monitoring

Lizzie Neumann
Department of Mathematics and Statistics
Helmut Schmidt University
Hamburg, Germany
neumannl@hsu-hh.de

Jan Gertheiss
Department of Mathematics and Statistics
Helmut Schmidt University
Hamburg, Germany
gertheij@hsu-hh.de

***Abstract*—When developing new systems for structural health monitoring of infrastructure buildings such as bridges, the structure to be monitored is typically equipped with various sensors and monitored through the data obtained. This sensor data, however, is often dependent on environmental influences such as temperature. In this paper, an approach for adjusting the corresponding covariances of sensor outputs by use of smooth/nonlinear, penalized regression splines is presented. For illustration, the method is applied to a rich, publicly available data set (OSIMAB).**

***Index Terms*—partial covariance, penalized regression splines, residualization, response surface model, sensor data, temperature effect**

I. Introduction

Structural health monitoring (SHM) uses sensor data from buildings such as bridges to detect, localize and/or quantify damage; compare, e.g., Ahlborn et. al. [1], Ou and Li [13] and Seo, Hu and Lee [15]. As these measurements are not obtained under laboratory conditions, the data are dependent on environmental influences such as temperature. Therefore, a model to adjust for these covariates, is required when analyzing the data.

Figure 1. Valley Bridge Sachsengraben [2]

A recent and very broad review of methods for SHM under varying temperature conditions is provided by Han et. al. [5]. With respect to forecasting and separating temperature-induced from structural responses, it is distinguished between input-output methods and output-only approaches. In the first case, both observations of the sensor output and confounding variables such as temperature are considered, while in the latter case, as the name tells, only the vibration or static (such as strain) responses of the structures are used, often employing projection methods such as principal component analysis (PCA), compare, e.g., Kromanis and Kripakaran [9], Wah et. al. [17] and Yan et. al. [21]. Wah, Chen and Owen [18], by contrast, proposed a method for vibration-based SHM data which uses a simple regression analysis where the vibration properties are used as independent and dependent variables. Therefore environmental and operational conditions are not needed for modeling. Among input-output methods, a very popular approach is to regress sensor measurements on environmental and/or operational variables, which is also known under the name *response surface* modeling. Then, following the so-called "subtraction method", the predicted sensor data is subtracted from the actually observed data, and the residuals are used for further analysis. For fitting regression function(s) to the data, various methods are available, ranging from simple linear or polynomial regression to advanced machine learning approaches such as support vector machines or artificial neural networks; see, e.g., Jin et. al. [7], Kromanis and Kripakaran [8], Ni et. al. [11] and Zhou, Ni and Ko [22]. In this paper, we will present a nonlinear regression technique using penalized splines, which is a very popular approach in semiparametric statistics for fitting nonlinear regression functions. Those functions are obtained in a very flexible, data-dependent yet explicit, interpretable fashion; that means, not as a "black box" as it is often the case with other nonlinear machine learning algorithms.

We will illustrate our approach on the OSIMAB *(Online Safety Management System for Bridges)* [12] data set, which consists of sensor measurements of the valley bridge Sachsengraben on the motorway A45 in Germany. In Figure 1 a picture of the bridge is shown. Among other things, strain was measured with 28 strain gauges in 100 hertz and temperature with ten structure temperature sensors and one outer temperature sensor in 1 hertz from January 1st 2020 to August 1st 2021. The strain data was downsampled to 1 hertz. Table I provides an overview of the strain sensors we used and how they are named in the OSIMAB data set [12].

The northern superstructure of bridge is divided into three fields with two positions in field 1 and 3 and three positions in field 2. The strain senors are evenly distributed on the

https://doi.org/10.24405/14566

TABLE I
NAMES OF STRAIN SENSORS

here	OSIMAB data set
1	N_F1_SG_1_NO
2	N_F1_SG_1_NU
3	N_F1_SG_1_SO
4	N_F1_SG_1_SU
5	N_F2_SG_1_NO
6	N_F2_SG_1_NU
7	N_F2_SG_1_SO
8	N_F2_SG_1_SU
9	N_F2_SG_2_NO
10	N_F2_SG_2_NU
11	N_F2_SG_2_SO
12	N_F2_SG_3_NO
13	N_F2_SG_3_NU
14	N_F2_SG_3_SO
15	N_F3_SG_1_SU
16	N_F3_SG_2_NO
17	N_F3_SG_2_NU
18	N_F3_SG_2_SO
19	N_F3_SG_2_SU

left (north) and right (south) sides of the bridge. At each position four strain gauges, two on the northern and two on the southern side, are appliqued on the lower strap and on the bar as shown in FIGURE 2. The structure temperature sensors are in a hollow box beneath the roadway arranged as shown in FIGURE 3. We used the first and 10th temperature sensor for our analysis. Temperature sensor 1 is in the middle of the street eastwards between strain sensor 1 and 3, and temperature sensor 10 is to the east of strain sensor 1.

For illustrating the effect of response surface modeling in the OSIMAB data, we will use covariances as a measure of association between sensor outputs. That is why we will first motivate the approach from the perspective of conditional and partial covariances in Section II. Section III then presents the basics of penalized regression splines. Application to OSIMAB is found in Section IV, and Section V concludes.

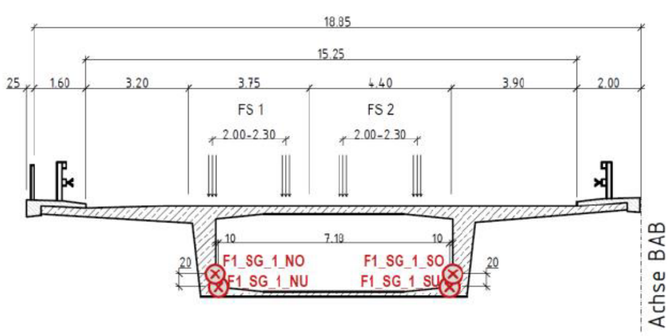


FIGURE 2. STRAIN SENSOR IN POSITION 1 OF FIELD 1 [16]

II. CONDITIONAL AND PARTIAL COVARIANCE

Let u and v be two random variables describing two different sensor outputs and let z denote a potentially confounding

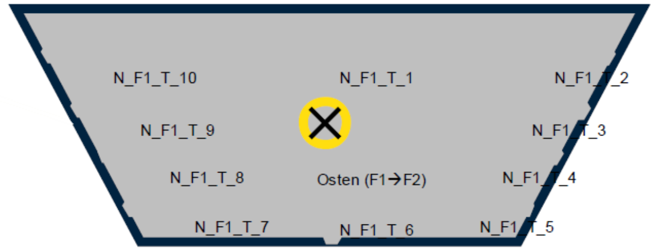


FIGURE 3. TEMPERATURE SENSORS [16]

covariate, such as temperature. First, let us assume that u, v and z are jointly normal, i.e.

$$\begin{pmatrix} u \\ v \\ z \end{pmatrix} \sim N\left(\begin{pmatrix} \mu_u \\ \mu_v \\ \mu_z \end{pmatrix}, \begin{pmatrix} \sigma_{uu} & \sigma_{uv} & \sigma_{uz} \\ \sigma_{vu} & \sigma_{vv} & \sigma_{vz} \\ \sigma_{zu} & \sigma_{zv} & \sigma_{zz} \end{pmatrix}\right). \tag{1}$$

Further let

$$\mu_{uv} = \begin{pmatrix} \mu_u \\ \mu_v \end{pmatrix}, \quad \Sigma_{uv} = \begin{pmatrix} \sigma_{uu} & \sigma_{uv} \\ \sigma_{vu} & \sigma_{vv} \end{pmatrix}, \quad \Psi = \begin{pmatrix} \sigma_{uz} \\ \sigma_{vz} \end{pmatrix}.$$

Then for the conditional distribution of (u, v) given z we have

$$\begin{pmatrix} u \\ v \end{pmatrix} |z \sim N\left(\mu_{uv} + \frac{1}{\sigma_{zz}}\Psi(z - \mu_z), \Sigma_{uv} - \frac{1}{\sigma_{zz}}\Psi\Psi^\top\right).$$

For estimating the *conditional* covariance of u and v given z

$$\sigma_{uv|z} = \sigma_{uv} - \frac{\sigma_{uz}\sigma_{vz}}{\sigma_{zz}},$$

we can use the empirical versions of σ_{uv}, σ_{uz}, σ_{vz} and σ_{zz}.

Alternatively, u and v can be regressed on z, and then we can calculate the covariance of the residuals. This approach is known under the name *partial* covariance. In fact, the covariance of u and v after being regressed on z in a linear way is consistent with the conditional covariance if we assume a joint, trivariate normal distribution of (u, v, z), because then:

$$\begin{aligned} &E\left(\left(u - \left(\mu_u + \frac{\sigma_{uz}}{\sigma_{zz}}(z - \mu_z)\right)\right)\right. \\ &\left.\left(v - \left(\mu_v + \frac{\sigma_{vz}}{\sigma_{zz}}(z - \mu_z)\right)\right)\right) \\ &= \sigma_{uv} - \frac{\sigma_{uz}\sigma_{vz}}{\sigma_{zz}}. \end{aligned}$$

However, assuming joint normal distribution (1) for the derivation of the conditional covariance and the use of linear regression for partial covariance might be too restrictive. Therefore, as a generalization of the partial covariance approach, we may allow nonlinear regression functions $f_u(z)$ and $f_v(z)$ when modeling the association between the sensor outputs u and v and the covariate z, respectively. Then we have for the sensor outputs u and v

$$\begin{aligned} u &= f_u(z) + \epsilon, \\ v &= f_v(z) + \xi, \end{aligned} \tag{2}$$

and the *partial* covariance is calculated as the covariance of the residuals ϵ and ξ.

As already sketched in the Introduction, various methods are available for fitting the (non-)linear regression functions $f_u(z)$ and $f_v(z)$ to the data. Ni et. al. [11], for instance, used support vector machines (SVM) with a linear estimation function and compared the results with those of a (multivariate) linear regression model. Specifically, they used SVM to formulate regression models which quantify the effect of temperature on modal frequencies of vibration data. In their studies, the data set is divided into a training and a validation set and the squared correlation coefficient is used as a measure of the model performance under different SVM coefficients. But they claim that the prediction of a model with SVM coefficients optimized by the training data is bad. Worden and Cross [20] used a Bayesian Treed Gaussian Process (TGP) model to represent pre-processed vibration-based SHM data (natural frequencies) as a function of temperature, wind and traffic load. The TGP approach, however, is computationally expensive and Worden and Cross only considered data with the number of sampling instances in the hundreds or thousands (thanks to pre-processing through natural frequencies). In what follows, we will present our penalized spline approach that can deal easily with high-dimensional data as given with OSIMAB.

III. Penalized Regression Splines

Our proposal for estimating $f_u(z)$ and $f_v(z)$ is penalized regression splines as implemented in R-package `mgcv` [14], [19]. Generally speaking, those functions $f : \mathcal{T} \to \mathbb{R}$ are of the form

$$f(z) = \sum_{k=1}^{q} b_k(z)\beta_k, \tag{3}$$

where $b_1(z), \dots, b_q(z)$ are (pre-specified) basis functions and $\beta_1, \dots, \beta_q$ are corresponding basis coefficients that need to be estimated from the data. $\mathcal{T}$ is a sensible subinterval of $\mathbb{R}$ containing the z-values observed in the data. A popular choice for the basis is cubic B-splines; compare, e.g., Eilers and Marx [4]. If both the predictor z and the response, let's say u, are available for n data points in terms of (u_i, z_i), $i = 1, \dots, n$, basis coefficients β_k from (3) can, for instance, be estimated through least-squares. That means, we have to minimize the function

$$Q(\boldsymbol{\beta}) = \|\mathbf{u} - \mathbf{f}_u\|^2 = \sum_{i=1}^{n} \left(u_i - \sum_{k=1}^{q} b_k(z_i)\beta_k \right)^2,$$

with $\boldsymbol{\beta} = (\beta_1, \dots, \beta_q)^\top$, $\mathbf{u} = (u_1, \dots, u_n)^\top$, $\mathbf{f}_u = (f_u(z_1), \dots, f_u(z_n))^\top$, and closed form solution

$$\hat{\boldsymbol{\beta}} = (B^\top B)^{-1} B^\top \mathbf{u}.$$

Here, B is an $(n \times q)$ design matrix with $(B)_{ik} = b_k(z_i)$.

However, for being sufficiently flexible with respect to the types of functions f that can be fitted/approximated through (3), typically a relatively large number q of basis functions needs to be chosen. If then fitted via ordinary least squares the estimated β_k, and hence the resulting f, tend to be wiggly and hard to interpret. A common remedy is to add a smoothing penalty when fitting f, resp. $\beta_1, \dots, \beta_q$. A popular choice is to penalize curvature in term of the integral of the squared second derivative for f. Specifically, the following applies

$$\int_{\mathcal{T}} f''(z)^2 dz = \boldsymbol{\beta}^\top \Omega \boldsymbol{\beta}$$

where Ω is a penalty matrix whose concrete form depends on the basis being chosen; compare, e.g., Lancaster and Salkauskas [10]. Model (2), resp. $\boldsymbol{\beta}$, is then estimated by *penalized* least squares in terms of minimizing

$$\|\mathbf{u} - \mathbf{f}_u\|^2 + \lambda \boldsymbol{\beta}^\top \Omega \boldsymbol{\beta},$$

with closed form solution

$$\hat{\boldsymbol{\beta}} = (B^\top B + \lambda\Omega)^{-1} B^\top \mathbf{u}.$$

The procedure for v, resp. f_v, or outputs of further sensors, is completely analogous. The strength of the penalty, i.e., the amount of smoothing, is controlled through parameter λ, which should be chosen in a data-dependent fashion (compare Section IV). Then, further analyses are based on the residuals ϵ and ξ from (2), which is also known under the name (univariate) "residualization". In the following Section IV, we will consider the OSIMAB data and focus on the partial covariance as being estimated through the (empirical) covariance of the residuals resulting from penalized spline regression as described above.

IV. OSIMAB

The data from January 1st 2020 to August 1st 2021 of strain sensor 1 and temperature sensors 1 and 10 are shown in Figure 4. Looking at it, the strain is apparently dependent on the temperature. Therefore, for estimating the partial covariance, the data is modeled as in (2) where the response variables u and v are the outputs of two strain sensors, the covariate z is the output of temperature sensor 1 or 10, respectively; and f_u and f_v are the corresponding penalized cubic regression splines. K-fold cross-validation is used to determine the smoothing parameter and the `gam` function from `mgcv` is used to fit the model. K-fold cross-validation means that the data set is divided into K (roughly) equally sized segments, and it is iterated over those segments. In each of the K iterations, K-1 sets are used for training the model(s), and the set left out serves for validation and calculating the prediction error of each fitted model, compare, e.g., Hastie, Tibshirani and Friedman [6]. The obtained K prediction errors are then combined, and we can choose the smoothing parameter that minimizes this quantity. We allow smoothing parameters to vary across sensors.

Figure 5 shows the regression functions for the first strain sensor regressed on the first and 10th temperature sensor, respectively. Except for temperatures around zero, those functions appear rather linear, which indicates that also a simple (linear) regression model might be sufficient here. Nevertheless, the partial covariance could be different from the marginal

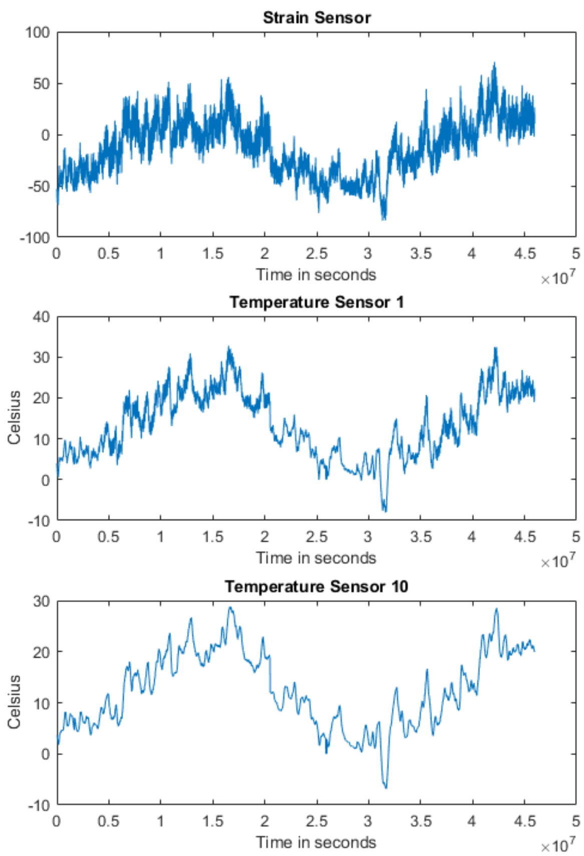


FIGURE 4. STRAIN (SENSOR 1) AND TEMPERATURE (SENSOR 1 AND 10) DATA

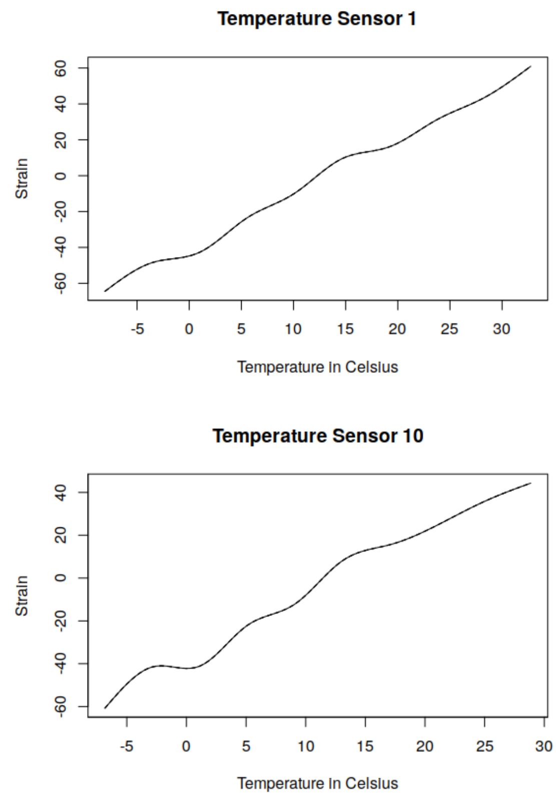


FIGURE 5. PLOT OF REGRESSION FUNCTIONS FOR FIRST AND 10TH TEMPERATURE SENSORS (FIRST STRAIN SENSOR)

one which results from the strain sensor output if ignoring temperature. In FIGURE 6 the covariance of the full strain data (19 sensors, compare TABLE I) without taking temperature into account, i.e., the marginal covariance (top), and the partial covariance, i.e. the covariance of the residuals, is shown in dependency of the first (center) and 10th (bottom) temperature sensor, respectively. Indeed, there seem to be some rather structural differences between the marginal covariance (top) and the partial version if regressed on temperature sensor 1 and 10, respectively. The change in the structural appearance is more important than the magnitude of the covariance because the covariance is not a normalized measure.

V. DISCUSSION AND OUTLOOK

Our analyses showed that covariances of sensor outputs may change depending on environmental factors such as temperature. Ignoring this can be harmful, in particular if the SHM system uses output covariances to detect potential damage. The presented approach of using response surface modeling and partial covariances, however, still has some potential shortcomings and limitations that we hope to resolve as part of our future research. First, and even if all potential confounders are known/observed, there are potential confounding effects on the covariance of sensor outputs that may be missed by response surface modeling and subsequent residualization. We are hence planing to switch from partial covariances to conditional ones estimated in a data-driven and flexible/nonparametric way.

Second, response surface modeling as done here (and often in the literature) ignores that sensor outputs may be correlated over time and exhibit some recurring daily pattern that might be due to unobserved confounding. Ignoring the correlation when fitting the regression functions through ordinary least squares, common maximum likelihood, or a similar, e.g., Bayesian, approach that assumes conditional independence between measurements, will typically lead to less accurate estimates and, more importantly, biased measures of statistical uncertainty such as confidence or prediction intervals. In SHM, the latter can be particularly harmful if those intervals are used for detecting if measurements are “out of control”. In addition, besides the environmental and operational factors that are monitored, there might be other confounders whose values are not observed and hence not available for an input-output method, which makes output-only methods an attractive alternative. To attack the problem of correlation, recurring daily patterns and unobserved confounding, we plan to develop a functional data framework for SHM that combines an input-output method for correlated and partly/potentially periodic data (function-on-function regression) with an output-only approach (functional principal components analysis) in a sound and interpretable way.

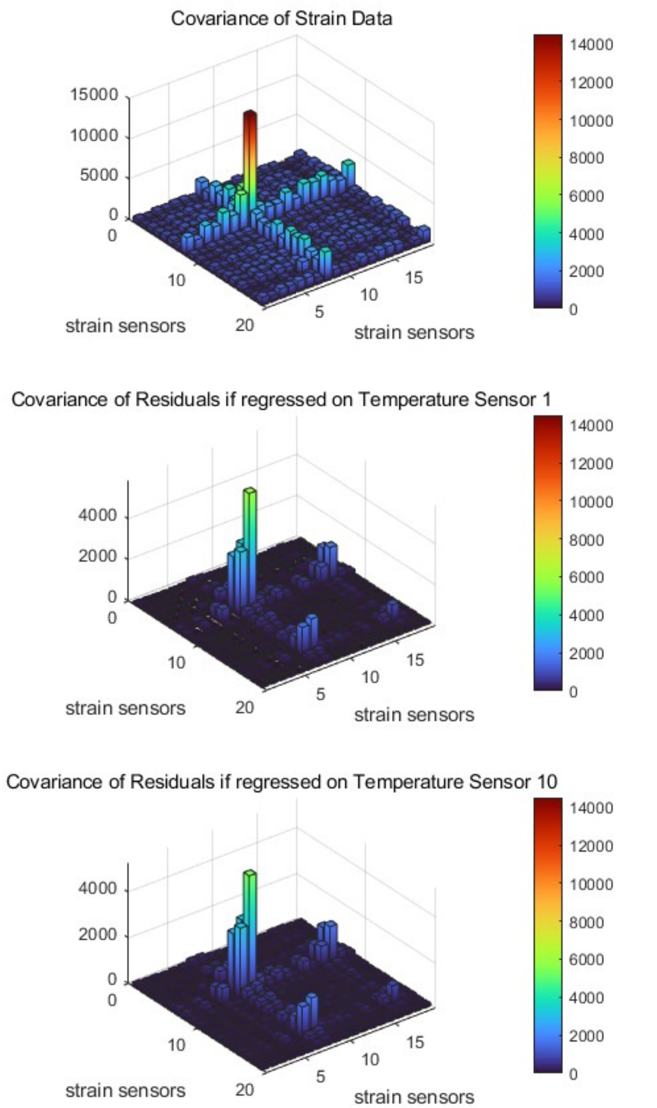


FIGURE 6. COVARIANCE OF THE STRAIN DATA AND RESIDUALS (TEMPERATURE SENSOR 1 AND 10)

ACKNOWLEDGMENT

This research paper out of the project SHM – Digitalisierung und Überwachung von Infrastrukturbauwerken is funded by dtec.bw - Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge.

REFERENCES

[1] T.M. Ahlborn, R. Shuchman, L.L. Sutter, C.N. Brooks, D.K. Harris, J.W. Burns, K.A. Endsley, D.C. Evans, K. Vaghefi and R.C. Oats, The State-of-the-Practice of Modern Structural Health Monitoring for Bridges: A Comprehensive Review, The National Academies of Sciences, Engineering, and Medicine, url = http://www.mtri.org/bridgecondition/doc/State-of-PracticeSHMforBridges(July2010).pdf, 2010.

[2] Bundesanstalt für Straßenwesen, Intelligente Brücken. url = https://www.bast.de/Forschungsplanung/DE/Verkehrsinfrastruktur/Beiträge/I-Bruecken.html?nn=2965460, 2016.

[3] M. Döhler, F. Hille, L. Mevel and W. Rücker, Structural health monitoring with statistical methods during progressive damage test of S101 Bridge. In: Engineering Structures 69, pp. 183-193. doi = https://doi.org/10.1016/j .engstruct.2014.03.010, url = https://www.sciencedirect.com/science/article/pii/S01410296140 01631, 2014.

[4] P. Eilers and B. Marx, Flexible Smothing with B-Splines and Penalties, Statistical Science, Vol. 11, No. 2, p. 89-121, 1996.

[5] Q. Han, Q. Ma, J. Xu and M. Liu, Structural health monitoring research under varying temperature condition: a review, In: Journal of Civil Structural Health Monitoring, p. 149-173, 2021.

[6] T. Hastie, R. Tibshirani and J. Friedman, The Elements of Statistical Learning: Data Mining, Inference, and Prediction, Second Edition, Springer Series in Statistics, Springer New York, NY, doi = https://doi.org/10.1007/978-0-387-84858-7, 2009.

[7] C. Jin, S. Jang, X. Sun, J. Li and R. Christenson, Damage detection of a highway bridge under severe temperature changes using extended Kalman filter trained neural network, J Civ Struct Health Monit 6(3):545–560, doi = https://doi.org/10.1007/s1334 9-016-0173-8, 2016.

[8] R. Kromanis, P. Kripakaran, Support vector regression for anomaly detection from measurement histories, Adv Eng Inform 27(4):486–495, doi = https ://doi.org/10.1016/j .aei.2013.03.002, 2013.

[9] R. Kromanis, P. Kripakaran, SHM of bridges: characterising thermal response and detecting anomaly events using a temperature-based measurement interpretation approach, J Civ Struct Health Monit 6(2):237–254, doi = https://doi.org/10.1007/s13349-016-0161-z, 2016.

[10] P. Lancaster and K. Salkauskas, Curve and Surface Fitting: an introduction, London: Academic Press, 1986.

[11] Y.Q. Ni, X.G. Hua, K.Q. Fan and J.M. Ko, Correlating modal properties with temperature using long-term monitoring data and support vector machine technique. In: Engineering Structures 27, pp. 1762–1773. doi = 10.1016/j .engstruct.2005.02.020, 2005.

[12] OSIMAB mCLOUD, text of license: http://www.govdata.de/dl-de/by-2-0, url = https://www.mcloud.de/downloads/mcloud/0489759B-1168-4EF5-A26D-488DE44816FE/osimab_sample.zip, 2020.

[13] J. Ou, and H. Li, Structural Health Monitoring in mainland China: Review and Future Trends, Structural Health Monitoring, 9(3), 219–231, https://doi.org/10.1177/1475921710365269, 2010.

[14] R Core Team, R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. url = https://www.R-project.org/ 2021.

[15] J. Seo, J.W. Hu and J. Lee, Summary Review of Structural Health Monitoring Applications for Highway Bridges, Journal of Performance of Constructed Facilities, American Society of Civil Engineers, doi = https://doi.org/10.1061/(ASCE)CF.1943-5509.0000824, 2016.

[16] Verbundprojekt OSIMAB (Online Sicherheits-Mangementssystem für Brücken) : Gesamtabschlussbericht, [Bundesanstalt für Straßenwesen (BASt), Abteilung Brücken- und Ingenieurbau], doi = https://doi.org/10.2314/KXP:1787930734 , 2021.

[17] W.S.L. Wah, Y.T. Chen, G.W. Roberts and A. Elamin, Separating damage from environmental effects affecting civil structures for near real-time damage detection, In: Struct Health Monit 17(4):850–868. https ://doi.org/10.1177/14759 21717 72206 0, 2017.

[18] W.S.L. Wah, Y.-T. Chen and J.S. Owen, A regression-based damage detection method for structures subjected to changing environmental and operational conditions, Engineering Structures 228. doi = https://doi.org/10.1016/j .engstruct.2020.111462, 2021.

[19] S. Wood, Generalized Additive Models: An Introduction with R, 2 edition. Chapman and Hall/CRC, 2017.

[20] K. Worden and E.J. Cross, On switching response surface models, with applications to the structural health monitoring of bridges. In: Mechanical Systems and Signal Processing 98, pp. 139–156. doi = http://dx.doi.org/10.1016/j .ymssp.2017.04.022, 2018.

[21] A.M. Yan, G. Kerschen, P. DeBoe and J.-C. Golinval, Structural damage diagnosis under changing environmental conditions—part 1: linear analysis, J Mech Syst Signal Process 19(4):847–864, https ://doi.org/10.1016/j .ymssp .2004.12.002, 2005.

[22] H.F. Zhou, Y.Q. Ni and J.M. Ko, Eliminating temperature effect in vibration-based structural damage detection, J Eng Mech 137(12):785–796, doi = https://doi.org/10.1061/(ASCE)EM.1943-7889.00002 73, 2011.

SmartShip - AI-based assistance systems for the maritime sector

Pavle Ivanovic[1], Jonas J. Schöttler[2], Alexander Windmann[2], Philipp Neumann[1]
[1]*Chair for High Performance Computing*
[2]*Chair for Computer Science in Mechanical Engineering*
Helmut-Schmidt-Universität / University of the Federal Armed Forces
Hamburg, Germany
SmartShip@hsu-hh.de

***Abstract*—Modern ships, equipped with various sensors, devices of communications, etc., could produce vast amounts of data that should be efficiently collected, processed, and analyzed in order to fully unlock their operational potentials for prospective maritime activities. The project SmartShip explores how artificial intelligence (AI) can assist in search and rescue missions by expanding digital capabilities of ships and improving the decision making efficiency of operators. In this paper, we investigate the state-of -the-art of smart ships on technology development, explore the current state of the project, explain the types and formats of collected data and provide the first sensor analysis. Furthermore, a draft for the software and hardware architecture is detailed, emphasizing system scalability and platform independence. Finally, the paper explains how to use and process the ship's data to build an AI-enhanced system for condition monitoring and person detection that should assist in locating people in offshore distress.**

***Index Terms*—Artificial Intelligence, Condition Monitoring, Cyber-physical Systems, Object Detection**

I. Introduction

Maritime shipping is becoming increasingly complex. Not only has the sheer volume of shipping increased by around 300 percent over the last thirty years[1]and is forecast to grow by around 250 percent over the next few decades[2], but the complexity of individual ships has also increased. Whereas ships were operated manually in the past, today a multitude of sensors control their success on board. However, managing vast numbers of multi-vendor sensor devices, interfaces, protocols, and connectivity options requires the reorganization of the traditional data acquisition approach by putting more emphasis on data standardization. Also, new hardware and software solutions need to conform to several criteria, such as limited onboard space and power, reliability, efficient onboard/fleet scaling, and effective data processing. On the other hand, increased system complexity leads to situations where the evaluation and overview of these sensors can no longer be managed without digital aids. This is where the SmartShip project comes in and supports the crew and the inland coordination centers with systems such as condition monitoring, object detection, and network connections.

[1]wiwo.de: Drastische Zunahme seit 1992 setzt Ozeane unter Druck
[2]eskp.de: Rasante Entwicklung im Flug- und Schiffsverkehr

Condition monitoring can be operated in different ways. The simplest approach would be the empirical vibration evaluation of moving parts, e.g. the motor. However, the knowledge gained from this analysis is limited and no longer does justice to a system with complexity of a modern ship. For this reason, we present in this paper a machine learning (ML) based system that evaluates operational data from hundreds of sensors and derives condition monitoring. These systems can be used, for example, to optimize maintenance intervals and reduce costs by only replacing parts when the predicted service due time has already been approached. In this way, maintenance is more efficient and can also save valuable resources. At the same time, components that are already worn out and thus pose a risk to the system can be replaced before the planned maintenance. Correspondingly, the operational readiness of a ship is always guaranteed.

Systems for tracking objects in the water can help to better and more quickly locate people in distress during a man overboard maneuver or search and rescue (SAR) operations. Particularly useful is the combination with infrared (IR) data, which allows the crew to locate people even in bad weather conditions, such as fog, heavy rain, high waves, or strong winds. Previous solutions for people detection usually comprised personal engagement where crew members stood on the cams or bridges and used binoculars to scan the area. If camera systems were engaged, they would have to be operated manually and there was no digital evaluation of the video feed. We therefore present a solution that can automatically locate and track people and rescue assets in the water by leveraging the sensor fusion of electro-optical (EO) and IR data. As a result, the search supported by ML introduces an additional safety factor and a fallback for the mandatory manual search by the crew.

The rest of the paper is structured as follows. In Section II, the first results of the data analysis are presented and the future direction of condition monitoring in SmartShip is described. Section III explains how to use object detection algorithms to assist in search and rescue missions. In Section IV, a draft for the software and hardware architecture that generates the ship's data is presented. Finally, Section V

https://doi.org/10.24405/14567

concludes the paper and gives an outlook on the future direction of the project.

II. Condition Monitoring

In order to monitor the system's behavior, the machinery of a ship is equipped with sensors that track features like oil pressure or cooling water temperature. The current data are shown to the ship's crew that knows the expected values and can act if there is a deviation. However, the sensor values are changing dynamically and are highly correlated. As the number of sensors of the individual installed subsystems increases, it becomes harder to keep up. ML offers an opportunity to work through that data and assist the ship's crew with monitoring the condition of the ship [5]. The proposed approach can be separated into three phases: First, the state of the engine has to be identified in order to group the highly dynamic data. Second, for every state, anomalies that might signal a malfunctioning component have to be detected. Third, by working through the historic anomalies, patterns in the data can be detected and projected into the future, providing a guideline for maintenance routines.

A. Engine State Identification

In order to qualify particular system behavior as an anomaly, one needs to determine the so-called "normal" or expected performance metrics. However, dynamic change of system parameters typical for maritime rescue missions requires precise classification of the current SAR deployment phase. For instance, the high values of pressure and temperature gauges do not immediately indicate abnormal ship behavior, if the cruiser is in a top-speed mission mode. On the other hand, the same parameters would probably imply serious malfunction if the ship is stationed in a harbor.

There are several methods to identify the state of the engine. First of all, the states can be labeled due to some underlying feature. One of the parameters that could give a precise picture of the current engine state is the number of revolutions per minute (RPM). As depicted in Figure 1, four major phases of a typical cruising mission can be distinguished: Shut off (RPM $= 0$), neutral (RPM ≈ 600), acceleration/deceleration ($600 <$ RPM < 2300), and cruising speed (RPM ≈ 2300). However, if we observe the neutral engine state, there is a deviation from the expected (catalog) value of 600 RPM. This deviation is less than a few percent, if external factors, such as waves, are not exhibited. Nevertheless, the maximum neutral value is not reaching over 700 RPM, resulting in a fairly good upper threshold for setting the boundary between engine states.

Another way to derive the states is to cluster the data, for example by using the k-means algorithm, which can be seen in Figure 2. By using a statistical method or an ML algorithm, it is possible to identify the system state without requiring a domain expert to pick a characteristic feature and derive thresholds by hand. Furthermore, a more nuanced separation of the data is possible, as clusters can be formed

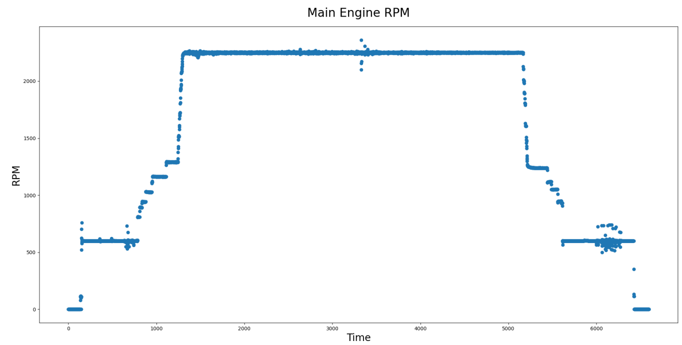


Figure 1. Main Engine RPM Measurements during Cruise Mission

over all features. However, most clustering algorithms struggle to separate time series data properly, which can also be seen in Figure 2. There are two distinct paths in the data: The lower path describes the data points during acceleration, and the upper path the data during deceleration, when the engine is heated. However, during high RPMs, these data are grouped together, as the algorithm has no information about the temporal context. Recently, there have been ML algorithms that learn the states together with their transitions [3], [7]. By clustering the time series data, the next steps can be performed much more efficiently.

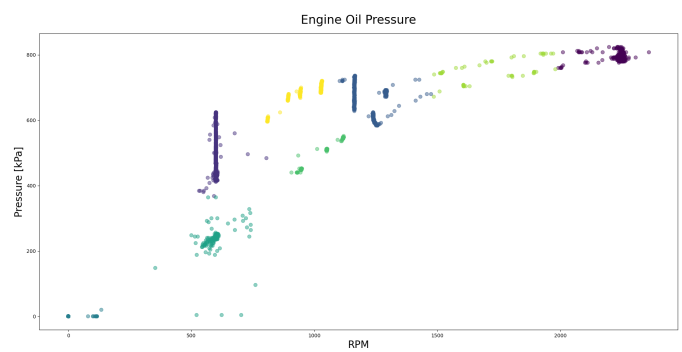


Figure 2. Main Engine Oil Pressure against RPM Measurements. In color: Clusters derived from the k-means algorithm.

B. Anomaly Detection

During the operation of the ship, certain ranges for the sensor values are expected, as they happen regularly and signal a well-functioning machine. Furthermore, the manufacturers of the machinery, in this case, Böning and MTU, provide tolerances of the sensor values that alert the crew when a threshold is crossed. There is, however, a problem when several subsystems interact: A slightly increased cooling water temperature might not be an anomaly on its own, but when the cooling water temperatures of all other subsystems are cooler than usual, it might indicate a deteriorating cooling system of the first machine and should be reported. With a high number of interacting subsystems, overseeing all sensors at once becomes increasingly difficult. To help with that, ML algorithms can be used to detect anomalies automatically [1]. The detection can be performed on live data or retrospectively on historic data, where they can help to gain new insights into the system. For example, a minor anomaly might be ignored during a SAR mission, as the engine works regardless. However, if this type of anomaly accumulates across several different ships of the same type, it might be worth investigating, as it might hint at a bigger problem. Thus, learning the behavior is not constrained to a single ship but can be expanded to a whole fleet in the future.

C. Predictive Maintenance

ML algorithms can use sensory machine data and information about maintenance routines in order to effectively predict the remaining useful life of a system [6]. However, in general information about how the maintenance has been performed and what parts had to be replaced is not available digitally. Therefore, detected anomalies can act as a guide on how maintenance could be improved. For example, if a certain type of anomaly only occurs in ships of the same type that operate in the north sea, maintenance routines for these ships should be adjusted, as future anomalies of the same kind are to be expected. Furthermore, by comparing data points to data of the same cluster, long-term trends can be detected and extrapolated, which allows to perform maintenance before failures occur.

III. Object Detection

In close, bilateral cooperation with the Wehrtechnische Dienststelle 71 (WTD71) for ships and naval weapons of the German Federal Armed Forces, Maritime Technology and Research, we have started field tests for the search and retrieval of persons and rescue equipment in the water. With several divers and various rescue equipment, accident victims were simulated and recorded with a state-of-the-art camera system. These images now serve as the basis for training the ML model to detect and track persons in distress.

In parallel, we use data from Naval Support Command (MUKdo) to classify naval vessels. Here the nation, type and capabilities of the ship are determined (according to NATO STANAG 1166). Another use case with the MUKdo is the classification of radar emitter.

A. Data

For the detection of people and rescue equipment, many hours of video footage are available, consisting of EO and IR recordings. These show divers and rescue equipment, as well as typical objects from the shipping industry. These include buoys, seabirds and drifting gear. The data were taken on different days in different weather conditions to create as much variety in the data as possible. Thus, the weather conditions change among the days from sunny and windless to wavy and overcast.

The data for ship classification shows ships and boats from various angles, from the horizontal perspective. The database consists of about 67,000 entries from most seagoing nations and shows units from small coastal patrol boats to aircraft carriers and submarines.

B. Conclusion

A pipeline is to be created for the detection and tracking of people and rescue equipment in the water, which receives both EO and IR data as a combined input (see Figure 3).

A pipeline for classifying nation, prefix and suffix has been created. This is the classification by multi-class problems for the nation and prefix and a multi-label multi-class problem for the suffix. This pipeline uses prior knowledge from the first network to flesh out subsequent outcomes.

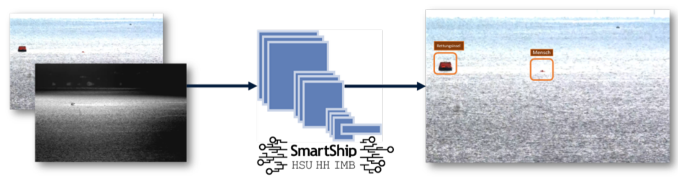


Figure 3. The schematic sequence for the detection of persons and rescue means is shown. On the left, the two video channels (EO and IR) are transferred to a neural network, which annotates the video feed and visually marks and classifies the victims. Here in the right picture on the left a life raft and on the right a WTD71 diver in a survival suit.

C. Experiments

Various networks of different sizes were tried to find the best converging network for object detection. The final model is based on the ResNet [4] architecture. Since the data set is very heterogeneous, different balancing solutions are tested. These include Stratifyer, Sampler and Loss-weights. The design of the classification task also turns out to be open to experimentation with respect to the multi-label-multi-class problem. Thus, combinations of classes as well as multi-hot vectors were used for this task.

IV. System Design

Condition monitoring and object detection tasks on ships require an optimal hardware/software solution to host the respective ML solvers, processing units and communication links (e.g. to sensors, camera, data). Therefore, we developed such an architecture and lay out its details in the following sections.

A. Hardware Optimization

The hardware architecture (Figure 4) is reflected in two distinctive implementations: edge (onboard) devices enhanced with LTE antennas and backend server, augmented with GPU accelerators. Onboard sensory data consists of three subsystems: Böning, MTU1, and MTU2. Böning metrics provide for the general ship data, such as indoor temperature, pressure, fuel levels, etc. while MTU represents engine parameters. Collected data proceeds via CAN [2] bus interface to the onboard unit (OBU), which acts as a data logger and simple forwarding device. However, our future upgrades will extend its capabilities with data processing which are important for several reasons. First, the majority of engine (MTU) sensors are in fact not implemented, although broadcasting the default values. Therefore, by filtering only relevant sensors, we can significantly reduce the LTE data loads. Second, OBU receives only raw data in CAN-compatible J1939 [8] format and the decoding is performed in the backend. If the decoding is moved to the OBU, the ML models could be run on the ship itself. Finally, by having direct access to the onboard raw data, we can calibrate and optimize data formats and decoding pipelines, improving thus the overall system efficiency.

In addition to built-in sensors, the camera module is being installed to allow critical objects/person detection in water. Besides optical and gyroscopic data, the visual parameters could be complemented with weather and AIS data, creating a comprehensive digital representation of vessel deployment conditions.

In addition to the OBU, we provide the NVIDIA Jetson units, complemented with solid-state drives (SSD). Jetsons are light, compact, and low-power GPU-accelerated devices, adapted to real-time condition monitoring and anomaly detection. Paired with selected 256GB SSDs, they allow for more than a month of uninterrupted raw data logging, which exceeds greatly typical rescue mission intervals (1-2 days).

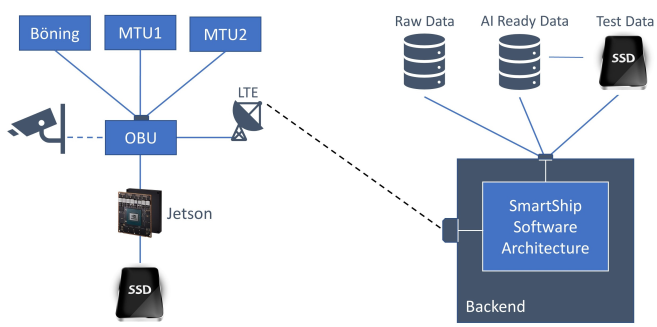


FIGURE 4. SMARTSHIP HARDWARE ARCHITECTURE

The server side is envisioned as the backbone for computationally heavy tasks, such as predictive maintenance (PM) model training, concurrent data processing, and fleet optimization. However, the exact implementation is not determined, as the hosting capabilities of the end user (DGzRS [3]) have to be defined first. Nevertheless, our system aims to be platform-independent by building on top of container software infrastructure. This approach provides great flexibility and the option to migrate the entire software stack from servers to the cloud and vice versa.

[3]German maritime search and rescue service

Also, regardless of the backend implementation, our solution allows for two high-capacity storage drives (raw/AI-ready), capable of one year of data logging each. In addition, the pre-production test environment envisions a third, faster SSD unit needed for experiments and model adjustments.

B. Software Architecture

The SmartShip software architecture (FIGURE 5) aims to provide a highly portable and platform-independent design that is easily adjustable to different edge/backend deployments. We achieve this by centralizing configuration options, allowing users to adapt the software stack to their own preferences. For instance, by selecting the appropriate data source, storage, and ML model, one can deploy the same system on a ship as well as on the backend server/cloud. In the following, we provide a short overview of the key software components.

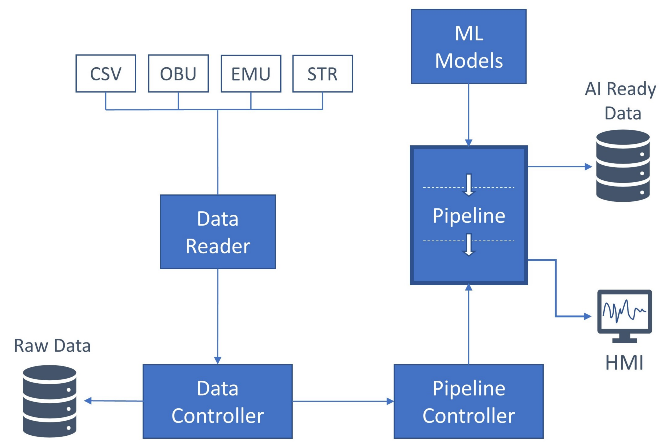


FIGURE 5. SMARTSHIP SOFTWARE ARCHITECTURE

Data Reader allows the selection of different sources (formats) of sensor data that should flow into the system: CSV logs, physical OBU interface, data emulator (EMU), or LTE stream (STR) of OBU raw data (FIGURE 4). However, in the production environment, CSV and OBU sources will converge into a single onboard interface while LTE streaming API remains as the backend connectivity option. After the source selection, the Data Reader notifies Data Controller if the new data is available and forwards it accordingly. Data Controller initiates storage of the Raw Data and signals the Pipeline Controller about the incoming traffic. Depending on the use case, deployment side, or user requirements, different ML models are engaged by the pipeline. Finally, Pipeline has two major outputs. In the first step, AI-ready data is created after initial raw data (pre)processing. Then, different ML models are called, allowing anomaly detection and predictive maintenance calculations. In the last step, based on user requests, data is visualized and displayed on maritime-certified screens. This modular approach allows a lot of flexibility in adding and removing different AI services without influencing the core software structure. In other words, by wrapping each new model into a new container, extra features could be added over time or even migrated to a different platform, if scaling up the system surpasses the customer hosting limitations.

V. Conclusion and Outlook

In this paper, we explained the goals of the SmartShip project and gave an overview of the essential research components, summarized by ML models for condition monitoring, offshore object detection, and a ready-to-deploy hardware/software solution. An initial analysis showed that the onboard sensory data can be efficiently clustered and separated according to the engine states, which is a precondition for effective anomaly detection. Also, we indicated that object tracking algorithms can combine both electro-optical and infrared signals to assist in search and rescue missions. Finally, our system design developments are demonstrated through the emulation of the actual sensory data, allowing real-time condition monitoring and engine state evaluation. However, further tests should be undertaken in order to improve the overall system efficiency, reevaluate the findings in the dedicated hardware and migrate the created AI tools into a near-production prototype. There may also be an extension towards other maritime companies and sea-based organizations, as well as further cooperation with other universities and research institutes.

Acknowledgment

This research project (SmartShip) is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr. The authors gratefully acknowledge discussion and exchange with project partners: German Maritime Search and Rescue Service (DGzRS), OptoPrecision GmbH and JAKOTA Design Group GmbH.

References

[1] Raghavendra Chalapathy and Sanjay Chawla. Deep learning for anomaly detection: A survey.

[2] Ricardo De Andrade, Kleber N. Hodel, João Francisco Justo, Armando M. Laganá, Max Mauro Santos, and Zonghua Gu. Analytical and experimental performance evaluations of can-fd bus. *IEEE Access*, 6:21287–21295, 2018.

[3] Vincent Fortuin, Matthias Hüser, Francesco Locatello, Heiko Strathmann, and Gunnar Rätsch. Deep self-organization: Interpretable discrete representation learning on time series. In *ICLR*, 2019.

[4] Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. *CoRR*, abs/1512.03385, 2015.

[5] Iraklis Lazakis, Konstantinos Dikis, Anna Lito Michala, and Gerasimos Theotokatos. Advanced ship systems condition monitoring for enhanced inspection, maintenance and decision making in ship operations. *Transportation Research Procedia*, 14:1679–1688, 2016.

[6] Jay Lee, Fangji Wu, Wenyu Zhao, Masoud Ghaffari, Linxia Liao, and David Siegel. Prognostics and health management design for rotary machinery systems—reviews, methodology and applications. *Mechanical Systems and Signal Processing*, 42(1-2):314–334, 2014.

[7] Henrik Steude, Alexander Windmann, and Oliver Niggemann. Learning physical concepts in cps: A case study with a three-tank system. *IFAC-PapersOnLine*, 55(6):15–22, 2022.

[8] W. Voss. *A Comprehensible Guide to J1939*. Copperhill Technologies Corporation, 2008.

Kapitel III
Kompetenzen für die digitale Arbeitswelt (KoDiA)

mit Beiträgen von

Bundesinstitut für Berufsbildung

Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

MEGWARE Computer Vertrieb und Service GmbH

Universität der Bundeswehr München

University of Education Freiburg

Vorwort zum dtec.bw-Dachprojekt „Kompetenzen für die digitale Arbeitswelt (KoDiA)“

Digitalisierung können wir heute verstehen als eine der großen kulturellen Umwälzungen der Zivilisation. Der Soziologe Dirk Baecker stellt sie in eine Reihe mit der Erfindung der Sprache, der Schrift und des Buchdrucks (Baecker 2017). Damit verbunden sind grundlegende Auswirkungen auf alle Bereiche unseres Alltagslebens. So erleben wir Digitalisierung in unserem Berufsleben, genauso wie im Privaten. Sie beeinflusst unser tagtägliches Handeln und auch wie wir unsere Welt wahrnehmen und interpretieren – oft genug, ohne dass wir das bemerken.

Im Dachprojekt „Kompetenzen für die digitale Arbeitswelt“ geht es deshalb um die Frage, was Digitalisierung mit uns Menschen macht, wie wir Digitalisierung ein- und umsetzen und welche Konsequenzen das für unser Zusammenleben in Gesellschaft, in Organisationen und in Gemeinschaft hat. Darüber hinaus wird in drei dem Dachprojekt zugeordneten Einzelprojekten erforscht, wie wir Digitalisierung aktiv und mündig mitgestalten können.

Die drei Einzelprojekte, die zum Dachprojekt KoDiA gehören, sind:

- „Entwicklung einer App für modulare Lerntherapie im Bereich Mathematik (AppLeMat)“, Prof.‘in Dr. Monika Daseking
- „Kompetenzplattform für Softwareeffizienz und Höchstleistungsrechnen (hpc.bw)“, Prof. Dr. Philipp Neumann
- „Kompetenzen für die digitale Arbeitswelt (KoDiA) – Ertüchtigung zur Digitalisierung“, Prof. Dr. Manuel Schulz und AkDir’in Dipl.-Päd. Andrea Neusius

Die Einzelprojekte sind interdisziplinär angelegt und vereinen pädagogische, psychologische und informationstechnische Forschungsfragen und -ansätze.

Aus bildungstheoretischer Sicht steht dabei eine kritische Auseinandersetzung mit den für die aktive und mündige Mitgestaltung der Digitalisierung erforderlichen Kompetenzen im Vordergrund. Wir verstehen Kompetenz in einem pädagogisch-emanzipatorischen Sinne, der über rein qualifikatorisch-funktionale Lernziele hinausreicht und mündige, zur verantwortlichen Mitgestaltung der Welt in der sie leben fähige Bürger:innen als zentrale Bedingung einer Gesellschaft ansehen, die resilient gegenüber Desinformation, Manipulation und antidemokratischer Polarisierung ist. In diesem Sinne erachten wir Bildungsarbeit und Bildungspolitik als fundamentalen Beitrag zu einem erweiterten Sicherheitsverständnis. Dieses hier nur grob skizzierte Forschungsinteresse- und -verständnis liegt in besonderer Weise dem gleichnamigen Einzelprojekt „KoDiA“ im Rahmen dieses Dachprojektes zugrunde.

Die inter- und transdisziplinäre Perspektive der am Dachprojekt KoDiA beteiligten Einzelprojekte, die Betrachtung der Dimensionen Bildung, Lernen und Informationstechnik sowie der stetige Austausch mit unseren Forschungspartnern in Wissenschaft und Anwendung sind für uns Antrieb und Mehrwert der gemeinsamen Forschung in dtec.bw und darüber hinaus.

Gemeinsam gewinnen wir ein besseres Verständnis davon, was genau unsere digitalisierte Arbeits- und Lebenswelt ausmacht, vor welche konkreten Herausforderungen sie uns stellt und wie wir Wege finden können, diese nicht nur adaptiv zu bewältigen, sondern kritisch-konstruktiv daran mitzuwirken.

Wir freuen uns darüber, dass auch aus dem Dachprojekt „KoDiA“ verschiedene Beiträge zu diesem Sammelband entstanden sind. Dafür danken wir den Autor:innen. Sehr herzlich danken wir auch Herrn Prof. Dr. Detlef Schulz für die Initiative zu diesem Sammelband, der uns die Chance bietet, unsere Forschungsansätze und bisher erzielten Erkenntnisse zu veröffentlichen. Für die hervorragende Unterstützung für eine einheitliche Formatierung unserer Beiträge gilt dem Redaktionsteam ebenfalls unser herzlicher Dank.

Wir sind sehr gespannt, wie es weitergeht und wünschen allen Leser:innen viel Freude dabei, die verschiedenen Projekte zu erkunden.

manuel schulz und Andrea Neusius

Einsatz und Praktikabilität von Applikationen und Software zur Förderung von Mathematikschwierigkeiten aus lerntherapeutischer Sicht

Lena Löffler*, Leon Skoba, Milena Richter, Monika Daseking
Pädagogische Psychologie
Helmut-Schmidt-Universität
Hamburg, Deutschland
*lena.loeffler@hsu-hh.de

***Kurzfassung* – Im Rahmen des BMVg dtec.bw-Projektes AppLeMat wurde eine qualitative Umfrage unter Lerntherapeut*innen mit dem Ziel durchgeführt, die Grundvoraussetzungen der Anwendung einer modularen Applikation in der Lerntherapie im Bereich Mathematik zu explorieren. Dabei wurde der aktuelle Einsatz von bereits vorhandenen und genutzten Applikationen in der Lerntherapie erfragt, die Stärken und Schwächen des Einsatzes identifiziert und die wichtigen Funktionen einer Applikation aus Sicht der Anwender*innen unter Anwendung der Qualitativen Inhaltsanalyse herausgearbeitet. Im Wesentlichen sind dies die Möglichkeit einer individuellen Aufgabengestaltung, Motivationsförderung durch die digitale Anwendung und der niedrigschwellige Zugang zur Förderung, z.B. für chronisch-kranke Kinder, die Schwierigkeiten haben, Lerntherapie vor Ort zu besuchen. Die Ergebnisse ebenso wie der aktuelle Forschungsstand fließen in die Entwicklung der Applikation zur modularen Lerntherapie im Bereich Mathematik ein.**

Stichworte – digitale Lerntherapie, Applikation, Mathematikschwierigkeiten, Dyskalkulie, Qualitative Inhaltsanalyse

Nomenklatur

App	Applikation
$BMVg$	Bundesministerium der Verteidigung
dtec.bw	Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr

I. Einleitung

Im März 2020 kam es aufgrund der Maßnahmen zur Eindämmung der Covid-19-Pandemie deutschlandweit zu einer plötzlichen Veränderung der Schul-, Betreuungs- und Fördersituation für Kinder und Jugendliche in Deutschland. Diese Veränderungen brachten außergewöhnliche Umstände für das Lehren und Lernen sowie die Förderung von Kindern mit Lernschwierigkeiten mit sich. Von einem auf den anderen Tag mussten auch neue, digitale Förderkonzepte geschaffen werden. Eine Studie von Engzell und Kollegen (2021) [1] zeigt, dass rein technologische Mittel und der Zugang dazu nicht ausreichend waren, um einen qualitativ-hochwertigen Unterricht ohne Lernverlust zu gewährleisten. Eine Studie von Meeter (2021) [2] konnte belegen, dass es beim Einsatz von spezieller Software z.B. SNAPPET aber keinen Lernverlust durch den Fernunterricht gab. Diese beiden Untersuchungen wurden in den Niederlanden durchgeführt. In Hamburg hat im Mai 2020 eine regionale Online-Befragung unter Eltern, Pädagog*innen und Schüler*innen stattgefunden, in der die subjektiven Einschätzungen der Lernsituation kurz nach dem ersten Lockdown erfragt wurden. Dabei zeigte sich, dass sich über die Hälfte der Lehrkräfte und Eltern Sorgen um den Lernstand der Schüler*innen machten. 74% der Eltern schätzten auch die Unterstützung von Kindern mit sonderpädagogischem Förderbedarf schlechter ein. Hinzu kommt, dass nur 41% der Lehrkräfte an Regelschulen angaben, dass sie wüssten, wie sie mit Kindern mit sonderpädagogischem Förderbedarf im Fernunterricht umgehen sollen. Für den Präsenzunterricht waren es 80% der Lehrkräfte [3].

Benavides-Varela und Kolleg*innen 2021 [4] konnten auf Basis einer Metaanalyse zeigen, dass digitale Förderprogramme - im Vergleich zu anderen Interventionen - die Mathematikleistungen von Kindern verbessern können, und zwar über alle Altersstufen hinweg.

Lenhard und Lenhard (2016) [5] stellten jedoch in ihrer Untersuchung fest, dass ein großer Teil der zu erwerbenden Lernsoftware nicht auf einer theoretischen Grundlage entwickelt wurde und nicht wissenschaftlich evaluiert wurde. Um zukünftig eine professionelle und wissenschaftlich evaluierte Förderung im Bereich Mathematik zu ermöglichen, entwickeln wir eine App, die möglichst gut an die Bedürfnisse der Praxis angepasst ist, Dafür haben wir in Vorbereitung eine Umfrage durchgeführt, aus der Ergebnisse zu folgenden Forschungsfragen berichtet werden:

1) Welche Aspekte der Mathematikförderung lassen sich digital mittels einer App gut umsetzen?
2) Welche Vorteile und welche Schwächen hat die digitale Mathematikförderung?
3) Was sind notwendige und was zusätzlich gewünschte Funktionen bei einer App zur digitalen Lerntherapie?

https://doi.org/10.24405/14568

Darüber hinaus sollen deskriptive Ergebnisse zum Nutzungsverhalten digitaler Anwendungen durch Therapiekräfte vorgestellt werden.

II. Methode

A. Durchführung und Erhebungsinstrument

Zwischen März und Mai 2021 wurde eine bundesweite Online-Befragung mit Hilfe der Plattform „Unipark" durchgeführt. Durch ein exploratives Vorgehen sollten Informationen über die Nutzung von Apps in der Lerntherapie erhalten und die Grundvoraussetzungen zur Nutzung von Apps in der Lerntherapie, Stärken und Schwächen des Einsatzes, sowie unverzichtbare Funktionen erfragt werden.

B. Erkenntnisinteresse und Studiendesign

Durch die Aktualität der Thematik konnte nicht auf bereits bestehende Erhebungsmethoden zurückgegriffen werden.

Die Fragen des Erhebungsinstruments waren zum Teil geschlossen, zum Teil offen formuliert. Dadurch wurden einerseits Fakten abgefragt und andererseits gab es offene Fragen, die Spielraum für eine explorative Auswertung ließen.

C. Ablauf der Befragung

Zur Rekrutierung wurden insgesamt 219 lerntherapeutische Praxen bzw. Praxisgemeinschaften per Mail angeschrieben mit der Bitte um Weiterleitung an Kolleg*innen. Die Emailadressen wurden über den FiL- Fachverband für integrative Lerntherapie oder den BVL–Bundesverband für Legasthenie und Dyskalkulie generiert. Außerdem wurden weitere Adressen auf offiziellen Homepages im Internet recherchiert, um sicherzustellen, dass Lerntherapeut*innen in allen Bundesländern angeschrieben werden konnten. Die E-Mail umfasste einen Link, der direkt zur Umfrage führte, die mit Hilfe eines mobilen Endgerätes oder eines Computers mit Internetzugang ausgefüllt werden konnte.

D. Stichprobe

An der Umfrage nahmen insgesamt 51 Lerntherapeut*innen (weiblich = 45,9 %; Alter: M= 50.4; SD = 8.6) mit einer durchschnittlichen Berufserfahrung von M = 12.7; SD = 7.1 Jahren teil.

E. Analysemethode

Die Antworten auf die geschlossenen Fragen wurden mit Hilfe des Programms SPSS (Version 27) analysiert. Die offenen Fragen wurden im Programm MAXQDA (Version 20) mittels der qualitativen Inhaltsanalyse nach Mayring (2015) [5] und Kuckartz (2016) [6] ausgewertet. Nach der initiierenden Textarbeit wurde die inhaltlich strukturierende qualitative Inhaltsanalyse durchgeführt [7]. Einige Kategorien wurden deduktiv im Zusammenhang gebildet, was in diesem konkreten Fall meint, dass die Fragestellung die Kategorien maßgeblich vorgibt. So gibt z.B. die Antwort auf die Frage: In welchem Altersbereich würden Sie einen Schwerpunkt im Einsatz von Apps zu Förderung von Mathematikfähigkeiten setzen? Und warum? die Kategorie „Altersbereich" vor. Andere Kategorien wurden induktiv nach Sichtung des Materials gebildet [7]. Ein Beispiel hierfür ist die Kategorie „Motivation im Zusammenhang mit digitaler Lernförderung"; dieser Aspekt wurde nicht explizit erfragt, jedoch von den Lerntherapeut*innen in ihren Antworten als Thema angesprochen. Mit dem erstellten Kategoriensystem wurde das gesamte Textmaterial von zwei Kodiererinnen unabhängig voneinander kodiert. Nach dem ersten Kodierdurchgang kam es bereits zu einer Übereinstimmung von 63% (Cohen's K = 0.63). Dieser Wert gilt nach Kuckartz (2018) [7] als gut. Um zu einer sehr guten Übereinstimmung (Cohen's K $\geqslant$ 0.8) zu gelangen wurden diskrepante Textstellen von den Kodiererinnen besprochen und durch die Methode des konsensuellen Kodierens [8] eine 100%ige Übereinstimmung erreicht.

III. Ergebnisse

A. Deskriptive Ergebnisse

Zunächst werden einige deskriptive Ergebnisse vorgestellt. Innerhalb der zugrundeliegenden Stichprobe nutzen bereits 39.2 % Lern- und Förder-Apps in der Therapie. Diese Personen waren im Durchschnitt 47.6 Jahre alt (SD = 8.5) und hatten eine durchschnittliche Berufserfahrung von 14.2 Jahren als Lerntherapeut*in. Die durchschnittliche Medienkompetenz wurde in Schulnoten mit gut eingeschätzt (M = 2.1; SD = .7). Prozentual mehr Personen der Stichprobe (58.8 %) empfehlen Lern- und Förder-Apps ergänzend als Hausaufgabe; diese Personen sind im Durchschnitt 48.55 Jahre alt (SD = 8.3), haben eine durchschnittliche Berufserfahrung von M = 13.7; SD = 7.4 und schätzen ihre Medienkompetenz ebenfalls als „gut" ein. (M = 2.3; SD = .8). Betrachtet man nur die Personen, die sich selbst in ihrer Medienkompetenz als gut und sehr gut einschätzen, dann nutzt fast die Hälfte der Personen Apps in der Therapie (48.5 %) und mehr als die Hälfte empfiehlt Apps ergänzend zur Therapie für Zuhause (60.6 %).

B. Qualitative Ergebnisse

Welche Aspekte der Mathematikförderung lassen sich digital mittels einer App gut umsetzen?

Tabelle I zeigt die Subkategorien zur Hauptkategorie *Aspekte (der Mathematikförderung)*, die in der analogen Mathematik-Förderung stattfinden und die auch im digitalen Format umzusetzen sind. Insgesamt wurden 190 Textstellen aus den 51 Dokumenten kodiert. Drei häufig genannte Kategorien waren: *Grundrechenarten* (24 Nennungen); *Einmaleins* (19 Nennungen); *Mengenerfassung* (19 Nennungen).

Tabelle I: Subkategorien der Hauptkategorie „Aspekte der Mathematikförderung"

Subkategorie	***Definition***	***Ankerbeispiele***
Alle Aspekte	umfasst Auffassungen, dass sich grundsätzlich alle Aspekte der analogen Förderung auch in der digitalen Förderung umsetzen lassen	„Ich denke alle" (38, Pos.7)
Bruchrechnen	umfasst alle Aspekte, die das Rechnen mit Brüchen (Zähler/Nenner) aufgreifen	„Übungen zum Bruchrechnen mit Erklärungen" (66, Pos. 1)
Einheiten umrechnen	umfasst das Arbeiten mit Maßeinheiten und deren Umrechnung	„Umrechnen von Einheiten" (65, Pos.7)
Zahlenzerlegung	umfasst das Zerlegen von Zahlen in Teilmengen	„Zahlenzerlegung" (62, Pos. 7)
Grundrechenarten	umfasst die Grundrechenarten, wie Addition, Subtraktion, Multiplikation und Division	„Automatisierung von Addition oder Aubtraktion bis 10" (53, Pos. 1)
1x1	umfasst das Arbeiten mit dem kleinen Einmaleins	„Einmaleins automatisieren" (89, Pos.7)
Faktenwissen	umfasst das Bearbeiten von mathematischen Textaufgaben	„Vor allem das Training von Faktenwissen" (49, Pos. 7)

TABELLE I (FORTGESETZT)

Subkategorie	*Definition*	*Ankerbeispiele*
Sachaufgaben	umfasst das Bearbeiten von mathematischen Textaufgaben	„Demonstration von Mathematisierung bei Sachaufgaben" (61, Pos. 7)
Zahlenstrahl	umfasst das Arbeiten mit dem Zahlenstrahl	„Zahlenstrahl" (42, Pos.7)
Mengenerfassung	umfasst das Erfassen und Verstehen von Mengen	„Mengenwahrnehmung " (72, Pos. 1)
Veranschaulichungen	umfasst Aspekte der grafischen Darstellung mathemtischer Phänomene	„Veranschaulichung" (44, Pos.7)
Stellenwert	umfasst das Arbeiten mit Stellenwertsystemen (Dezimalsystem und Binärsystem)	„Verständnis für Dezimalsystem" (80, Pos.7)
Geometrie	umfasst den Bereich der geometrischen Aufgaben (Figuren, Geraden und Winkel)	„Geometrieverständnis" (55, Pos. 7)
Rechenstrategien	umfasst das Anwenden und Erlernen von Rechenstrategien beim mathematischen Arbeiten	„Anwendung von im Vorfeld aufgebauten Strategien" (141, Pos.7)
Blitzrechnen/ Blitzerfassen	umfasst Aufgaben unter Zeitlimit und das schnelle Bearbeiten von Rechenaufgaben	„Blitzrechnen" (52, Pos. 1)
Sonstige	umfasst alle weiteren Aspekte des mathematischen Arbeitens, die nicht bereits genannt wurden	„zum Erlernen der Uhrzeit" (72, Pos. 1)

Welche Vorteile und welche Schwächen hat die digitale Mathematikförderung?

In der folgenden TABELLE II sind zunächst die Vorteile der digitalen Mathematikförderung abgebildet. Die Subkategorien werden definiert und mit einem Ankerbeispiel verdeutlicht. Die drei Subkategorien mit den meisten Nennungen sind: *Motivation* (16 Nennungen); *Flexibilität/Unabhängigkeit* (15 Nennungen) und *Interesse* (9 Nennungen).

TABELLE II: SUBKATEGORIEN DER HAUPTKATEGORIE "VORTEILE DER DIGITALEN MATHEMATIKFÖRDERUNG"

Subkategorie	*Definition*	*Ankerbeispiele*
Struktur geben	umfasst Aussagen, die etwas darüber aussagen, dass durch das digitale Format Matheaufgaben strukturiert werden können	„Die SchülerInnen sehen keine vollen Seiten mit Päckchen voller Aufgaben oder großen Texten vor sich, so fällt der Einstieg leicht (kein Berg von Arbeit)" (67, Pos. 7)
Fahrtweg entfällt	alle Aussagen, die sich positiv äußern über den fehlenden Fahrtweg zu Lerntherapie	„Ist örtlich unabhängig und kann daher gerade in Flächenregionen eine mathematische Lerntherapie überhaupt erst ermöglichen." (136,Pos.8)
Entlastung der Eltern	umfasst alle Aussagen, aus denen ersichtlich wird, dass die Eltern durch das digitale Format entlaste werden	„Entlastung der Eltern beim Üben" (66, Pos. 8)

TABELLE II (FORTGESETZT)

Subkategorie	*Definition*	*Ankerbeispiele*
Wiederholung	umfasst alle Aussagen die sich zum Thema Wiederholung äußern	„Wiederholung und Festigung ist oft sehr zeitraubend und in Präsenz nicht umsetzbar. Hier bieten Medien, die in Eigenregie durchführbar sind, gute Möglichkeiten." (55, Pos. 8)
Interesse	umfasst Aussagen die erläutern, dass das Interesse durch den Einsatz der digitalen Medien erhöht wird	„Abwechslungsreicher, ansprechender, beliebter, leichter akzeptiert bei Kindern" (130, Pos. 8)
Motivation	alle Aussagen, die beinhalten, dass die Motivation gesteigert wird	„Das kann meiner Meinung nach der Motivation und dadurch den Lerneffekt steigern" (62, Pos. 1)
Angstminderung	alle Aussagen, die im Zusammenhang mit Angstminderung durch den Einsatz digitaler Förderung stehen	Die SchülerInnen können für sich ohne die Präsenz einer anderen Person Misserfolge riskieren und Aufgaben im gänzlich eigenen Tempo durchführen und immer wieder erfolgreich lösen. So entstehen bei Schülern mit Leistungsängsten immer wieder kleine Erfolge, die sie in ihrem Kompetenzempfinden stützen können." (67, Pos. 8)
Flexibilität/Unabhängigkeit	Aussagen die sich über die Flexibilität und Unabhängigkeit äußern.	„Durch eine App kann das Kind/der Jugendliche dann üben, wenn Zeit und Ruhe dafür ist" (84, Pos. 8)
Zeitaspekt	Aussagen, die sich eindeutig rund um das Thema Zeit bewegen.	„Zeitmanagement - jederzeit, überall" (38, Pos. 8)
Individualität	Aussagen, die sich mit den individuellen Möglichkeiten der beschäftigen	„Mit einer App kann das Kind/der Jugendliche individuelle üben" (84, Pos. 7)
Keine	umfasst alle Antworten, aus denen ersichtlich wird, dass die Person keine Vorteile sieht.	„gar keine Vorteile. Es hat sogar Nachteile." (51, Pos.8)
Sonstige	umfasst Aussagen, die nicht eindeutig einer Kategorie zugeordnet werden konnten, jedoch wichtig erscheinen	„Ansonsten ist Digitalisierung heute eher Segen als Fluch" (146, Pos. 9)

In TABELLE III sind die Schwächen der Mathematikförderung aufgeführt; die drei am häufigsten genannten Subkategorien sind: Beziehungsebene (Nennungen 19) Einseitige *Sinnesmodalitäten/ fehlendes Material* (21 Nennungen), *keine Individualität* (14 Nennungen).

TABELLE III: SUBKATEGORIEN DER HAUPTKATEGORIE „SCHWÄCHEN DER MATHEMATIKFÖRDERUNG“

Subkategorie	***Definition***	***Ankerbeispiele***
Braucht (elterliche) Unterstützung	Aussagen darüber, dass die Eltern ihre Kinder unterstützen müssen, um die digitale Förderung zu nutzen.	„Erklärung sind notwendig, die Apps ist kein Wundermittel und einige Eltern denken mit der richtigen App lernt das Kind schon rechnen, es ist aber immer auch eine Begleitung nötig“ (88, Pos. 9)
Keine Ergebnis- und Verständniskontrolle	umfasst Aussagen, die bemängeln, dass es bei der digitalen Förderung keine Ergebnis- und Verständniskontrolle gibt, z.B. weil die Kinder alleine üben	„Fehler werden nur festgestellt, nicht aber die falschen Denkprozesse, die dazu geführt haben, analysiert“ (61, Pos. 9)
Keine Flexibilität	Aussagen, die bemängeln, dass es keine Flexibilität bei der digitalen Förderung gibt	„zu wenig flexibel“ (54, Pos. 9)
Medienkonsum	negative Äußerungen bezüglich des Medienkonsums durch das Nutzen der digitalen Förderung	„Die Kinder sind genug durch die Digitalisierung und Medienkonsum von der Realität abgekapselt und entfremdet“ (51, Pos. 12)
Keine Individualität	Aussagen, die bemängeln, dass durch digitale Förderung keine Individualität in der Lerntherapie möglich ist	„Sie kann nicht individuell sein und nicht dort ansetzen und bleiben - wo das Kind wirklich gerade steht“ (57, Pos. 9)
Strategiemangel	Aussagen, die benennen, dass durch digitale Förderung keine Strategien vermittelt werden	„Aufgaben können durch Zählmechanismen statt Strategien gelöst werden“ (55, Pos. 9)
Verständnisprobleme	Aussagen, die sich darauf beziehen, dass es zu Verständnisproblemen kommen kann.	„Aufgaben werden von schwachen Lesern oft nicht verstanden, wenn keine verbale Darbietung erfolgt“ (55, Pos. 9)
Konzentration	Aussagen, die sich negativ gegenüber der Konzentration äußern.	„bei Unaufmerksamkeit ist man recht machtlos auf die Distanz“ (89, Pos. 9)
Beziehungsebene		
- Emotionale Ebene	persönliche und psychosoziale Aspekte	„Wir sind Menschen und brauchen Lernpartner aus Fleisch und Blut, die uns empathisch zugewandt sind“ (67, Pos. 9)
- Rückmeldung	Rückmeldung der Lerntherapeut*innen	„Apps erklären (oft zu viel und zu lange) zeigen, (oft zu wenig und zu schnell) Apps fragen nicht nach, wie und ob der Stoff verstanden wurde...“ (86, Pos. 9)

TABELLE III (FORTGESETZT)

Subkategorie	***Definition***	***Ankerbeispiele***
Fehlendes therapeutisches Setting	Aussagen, die das therapeutische Setting von Lerntherapie bestärken und das Fehlen dieses bei der digitalen Lerntherapie bemängeln	„mit Lernen assoziiertes Setting fehlt“ (65, Pos. 9)
Veranschaulichungen	Aussagen, die deutlich machen, wie wichtig die Veranschaulichung in der Lerntherapie ist	„Anschauungsmaterial im Präsenzunterricht und in den digitalen Medien stimmen oft nicht überein“ (148, Pos. 9)
Einseitige Sinnesmodalitäten/ fehlendes Material	In der Lerntherapie werden oft Materialien eingesetzt, die in der digitalen Therapie fehlen.	„ein Vermitteln zwischen den drei Ebenen enaktiv, ikonisch, symbolisch muss in Präsenz erfolgen, z.B. sind jegliche Förderung von Maßeinheiten ohne direkten Bezug sinnlos, das gleiche gilt ebenso für Brüche, Geometrie, keine App ersetzt das Einsetzen und Wegnehmen von Tüdelchen im Steckbrett oder beim Bündeln die Zahnstocher und Bindfäden o.ä. Im Endeffekt ist es ja genau das, was den Kindern fehlt. Sie sollen sich alles nur noch mental vorstellen, aber diese Ebene erreicht man in der LT nur über das Handeln, da hilft auch keine App, da das kein reelles Anfassen ersetzen kann“ (41, Pos. 9)
Sonstige	Aussagen die wichtig erscheinen, jedoch nicht eindeutig zugeordnet werden können	„Es gibt auch immer zu viel Schnickschnack drumherum“ (139, Pos. 9)

Was sind notwendige und was zusätzlich gewünschte Funktionen bei deiner App zur digitalen Lerntherapie?

In der folgenden TABELLE IV sind die Subkategorien gelistet, die zur Hauptkategorie *Notwenige Funktionen* zusammengeführt worden sind. Die Subkategorien mit den meisten Nennungen sind: *Belohnungssystem* (24 Nennungen); *Individuelle Anpassung* (24 Nennungen) und *Qualität/ technische Funktion* (19 Nennungen).

TABELLE IV: ERGEBNISSE ZUR HAUPTKATEGORIE „NOTWENDIGE FUNKTIONEN“

Subkategorie	***Definition***	***Ankerbeispiele***
Qualität/technische Funktionen	umfasst alle technischen Einstellungen und Qualitätsmerkmale	„gute Bild-Auflösung“ (62, Pos.12)
Klare Instruktionen	umfasst sprachliche Anweisungen und eindeutige Erklärungen	„Klare, kurze Aufgabenstellung“ (42, Pos.10)
Belohnungssystem	umfasst den Einsatz eines verstärkenden Systems oder einzelnen Verstärkern	„Aufforderungscharakter durch Belohnungssysteme“ (44, Pos.11)
Motivation	umfasst die Verwendung motivierender Elemente in jeglicher Form	„Altersgerechte Motivation (Token)“ (61, Pos. 10)
Feedback	umfasst den Einsatz von Rückmeldung und Feedback	„Sofortige Rückmeldung ob richtig oder falsch“ (111, Pos.11)
Wiederholung	umfasst Funktionen, die der Wiederholung von Inhalten und Aufgaben dienen	„Wiederholung von Inhalten, die nicht richtig gelöst wurden“ (48, Pos.11)
Spielerischer Faktor	umfasst den Einsatz spielerischer Elemente und den Spaßfaktor	„Gerne auch spielerisch“ (115, Pos.10)
Abwechslung/Vielseitigkeit	umfasst den Einsatz abwechslungsreicher Elemente und eine große Auswahl an Aufgaben	„Variation der Aufgaben Formate“ (130, Pos.10)
Dokumentation Lernfortschritt	umfasst das Festhalten des Lernfortschritts und die Darstellung dieses Fortschritts	„Protokollbögen, Lernfortschritte aufzeichnen“ (70, Pos.7)
Individuelle Anpassung	umfasst alle Möglichkeiten der individuellen Anpassbarkeit	„Genaue Anpassung an den individuellen Lernstand“ (44, Pos.10)
Zusammenhang/Struktur	umfasst Aspekte, die den Aufbau und die Struktur betreffen	„logischer Aufbau -klare, wiederkehrende Struktur“ (56, Pos.10)
Sonstige	umfasst alle weiteren Aspekte, die nicht bereits genannt wurden	„eine solche App sollte dem aktuellen Standard entsprechen“ (62, Pos.12)

In der folgenden TABELLE V sind die zusätzlich gewünschten Funktionen aufgeführt, für die die gleichnamige Subkategorie herausgearbeitet wurde. Die häufigsten wurden genannt: *Erklärungen/Strategien* (8 Nennungen), *Datenzugriff* (7 Nennungen), *Zeitvorgaben/Pausen* (5 Nennungen) und *Hilfestellungen Eltern* (5 Nennungen).

TABELLE V: SUBKATEGORIEN DER HAUPTKATEGORIE „ZUSÄTZLICH GEWÜNSCHTE FUNKTIONEN“

Subkategorie	***Definition***	***Ankerbeispiele***
Einstiegstest	umfasst die Anwendung eines Tests zum Erfassen des Lernstandes	„Eingangsdiagnostik oder Lernstandserhebung (…) “ (88, Pos.10)
Erklärung Strategien	umfasst den Einsatz von Erklärungen und Erläuterung von Rechenwegen	„Kleine Tools mit Erklärungen zu bestimmten Rechenprozeduren oder Beispiele“ (49, Pos.11) „Rechenregeln sollten abrufbar sein“ (62, Pos.11)
Zeitvorgaben/Pausen	umfasst die Verwendung von zeitlichen Vorgaben und eine Funktion für festgelegte Pausen	„Hilfe zur zeitlichen Struktur: Pausen!“ (61, Pos.11) „Eine Zeitbegrenzung“ (146, Pos.9)
Zeitaufgaben	umfasst das Angebot von Aufgaben auf Zeit	„Zeitaufgaben“ (49, Pos.11) „Blitzrechnen mit individueller Zeitmessung“ (80, Pos.11)
Zusatzmaterial	umfasst das Angebot von zusätzlichen Lernangeboten und Lernunterstützungen	„Erklärvideos“ (55, Pos.11) „vielleicht bei den Malaufgaben einprägsame Lieder“ (62, Pos.10)
Austausch/Chatfunktion	umfasst alle Möglichkeiten des gemeinsamen Austauschs	„Vllt. eine Möglichkeit mit anderen zu chatten, um ggf. den Austausch zu ermöglichen“ (84, Pos.11)
Konzentrationsförderung	umfasst Angebote zur Förderung der Konzentration	„Konzentrationsförderung“ (68, Pos.11)
Datenzugriff	umfasst alle Einstellungen, die den Datenzugriff für Dritte (Eltern, Therapierende, Lehrer) möglich machen	„Es müsste ein Therapeuten-Einwirkungs- und Verfolgungsportal geben, auf das ich jederzeit zugreifen kann“ (57, Pos.11)
Hilfestellungen Eltern	umfasst alle Unterstützungsmöglichkeiten, die den Eltern für die Nutzung der App zur Verfügung gestellt werden	„Hintergrundinformationen für Eltern, ggf. ein Elterncoaching, wie mit der App zu arbeiten ist“ (88, Pos.11)
Sonstige	umfasst alle weiteren Aspekte, die nicht bereits genannt wurden	„die aktuelle Lerntherapeutenliste des BVL (Bundesverband der Lerntherapeuten)“ (86, Pos.11)

IV. DISKUSSION

A. Einordnung der Ergebnisse

Die veränderte Lehr- und Lernsituation während der Covid-19-Pandemie hat eine neue Form der Förderung bei Mathematikschwierigkeiten nötig gemacht. Dazu ist es wichtig, dass man nicht nur technologische Mittel einsetzen kann [1], sondern, dass es auf spezielle Software ankommt [2]. Um Grundvoraussetzungen für eine Fördermöglichkeit in Form einer App zu entwickeln, wurde daher zunächst eine Umfrage unter potentiellen Nutzer*innen durchgeführt.

Bei der Frage nach den *Aspekten*, die sich gut digital fördern lassen, zeigt sich, dass *Grundrechenarten*, *Einmaleins* und *Mengenerfassung* die häufigsten Nennungen waren und dass die meisten Antworten sich auf Basiswissen der Grundschule beziehen.

Die genannten *Vorteile* der digitalen Förderung sind, dass Kinder unabhängiger und flexibler Lernen können und vor allem Kinder, die beispielsweise aus infrastrukturell schwächeren Regionen kommen, eine bessere Anbindung haben können, oder überhaupt erst die Möglichkeit einer Lerntherapie bekommen, was in diesem Zuge auch die Eltern entlastet. Als weiterer Vorteil wird genannt, dass die Kinder unmittelbares Feedback bekommen, was das Interesse und die Motivation steigern kann und die Möglichkeit zahlreicher Wiederholungen bietet [9]. Ein überraschend genannter Aspekt war die Angstminderung, die durch das niederschwellige Angebot der digitalen Förderung ausgeht, die Kinder haben einen Raum, in dem sie zunächst nicht sozialer Kontrolle ausgesetzt sind und sich in angstfreien Situationen bewegen können. Dieser Aspekt ist bisher nicht erforscht und sollte in zukünftigen Studien berücksichtigt werden, weil bekannt ist, dass bei Lernstörungen häufig komorbid Ängste auftreten [10]. Ein ebenfalls genannter Aspekt ist die *Individualität*, dieser wird jedoch auch als Schwäche genannt, weswegen dieser Aspekt an anderer Stelle noch diskutiert wird.

Die Subkategorien, die bei der Kategorie *Schwächen* die meisten Nennungen bekommen haben, sind *Beziehungsebene*, *einseitige Sinnesmodalitäten/fehlendes Material* und *keine Individualität.* Diese Schwächen ergeben sich aus dem digitalen Format und können in der Entwicklung der App berücksichtigt werden, außerdem gibt es bereits erfolgreiche digitale Förderprogramme, dies konnten beispielsweise Li und Ma (2010) in einer Meta-Analyse zeigen [11].

Was bei Analysen zur Kategorie *Schwächen* im Vergleich zu den *Vorteilen* auffällt ist, dass teilweise Kategorien sowohl als Schwäche als auch als Vorteil genannt werden *(keine Flexibilität - Flexibilität; keine Individualität - Individualität)* Das macht sehr deutlich, dass es zum Thema des Einsatzes digitaler Medien in der Lerntherapie keine einheitlichen Ansichten gibt und es deutlich auf die Qualität der eingesetzten App ankommt, ob beispielsweise eine flexible Anpassung an die Bedürfnisse der Kinder möglich ist oder nicht und ob sich daraus eine individualisierte Förderung ergibt oder nicht.

B. Limitationen

An der Umfrage haben 51 Therapiekräfte teilgenommen. Dies ist für eine qualitative Auswertung eine angemessene Stichprobengröße, jedoch können daraus keine repräsentativen Schlüsse gezogen werden. Die Ergebnisse spiegeln ein Meinungsbild wieder und sind zur Entwicklung einer App zur Mathematikförderung sehr hilfreich, sollten aber nicht verallgemeinert werden.

C. Relevanz für die Praxis

Unsere Umfrageergebnisse zeigen, dass in der Praxis durchaus bereits Apps in der Lernförderung eingesetzt werden oder als Hausaufgabe zum Üben zu Hause empfohlen werden. Jedoch sind nur wenige Apps, die es käuflich zu erwerben gibt, auch wissenschaftlich evaluiert. Die Umfrage wurde als vorbereitende Studie im Projekt AppLeMat durchgeführt, das zum Ziel hat, eine App zu entwickeln, die Mathematikförderung auf Distanz ermöglicht. Dabei sollen die Kinder individualisiert Module von den Lerntherapeut*innen zur Verfügung gestellt bekommen und durch adaptive Aufgabengestaltung flexibel gefördert werden. In der App wird es zur motivationalen Unterstützung zudem einen spielerischen Teil geben, der auf dem Token-Prinzip beruht.

D. Fazit

Die Ergebnisse der Umfrage zeigen, dass es wichtig ist, im Entwicklungsprozess der App mit Therapiekräften zusammenzuarbeiten. Wir werden dieses Konzept an verschiedenen Stellen in der Entwicklung weiterhin nutzen, um so eine App zu entwickeln, die praxisnah und wissenschaftlich evaluiert in der Mathematikförderung zum Einsatz kommen kann.

DANKSAGUNG

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr.

LITERATUR

[1] P. Engzell, A. Frey und M. D. Verhagen, „Learning loss due to school closures during the COVID-19 pandemic.,“ *Proceedings of the National Academy of Sciences,* 2021.

[2] M. Meeter, „Primary school mathematics during Covid-19: No evidence of learning gaps in adaptive practicing results.,“ *Preprint, PsyArXiv,* 2021.

[3] T. Brändle und A. Albers, „Befragung Lernen in Zukunft: Ergebnisse einer Online-Befragung von Eltern, Pädagoginnen und Pädagogen sowie Schülerinnen und Schülern in Hamburg vom 29. Mai bis 7. Juni 2020“.

[4] S. Benavides-Varela, C. Z. Callegher, B. Fagiolini, I. Leo, G. Altoe und D. Lucangeli, „Effectiveness of digital-based interventions for children with mathematical learning difficulties: A meta-analysis.,“ *Computers & Education,* 2020.

[5] W. Lenhard und A. Lenhard, „Evidenzbasierte Förderung schulischer Fertigkeiten am Computer: Lernspiele mit Elfe und Mathis.,“ *Förderprogramme für Vor- und Grundschule,* pp. 87-114, 2016.

[6] P. Mayring, Qualitative Inhaltsanalyse: Grundlagen und Techniken, Beltz, 2015.

[7] U. Kuckartz, Qualitative Inhaltsanalyse: Methoden, Praxis, Computerunterstützung, Beltz Juventa, 2018.

[8] C. Hopf und C. Schmidt, „Zum Verhältnis von innerfamilialen sozialen Erfahrungen, Persönlichkeitsentwicklung und politischen Orientierungen: Dokumentation und Erörterung des methodischen Vorgehens in einer Studie zu diesem Thema,“ 1993.

[9] C. Burgers, A. Eden, M. D. van Engelenburg und S. Buningh, „How feedback boosts motivation and play in brain-training game,“ *Computers in Human Behavior,* pp. 94-103, 2015.

[10] L. Visser, G. Büttner und M. Hassenhorn, „Komorbidität spezifischer und psychischer Auffälligkeiten: ein Literaturüberblick,“ *Lernen und Lernstörungen,* pp. 7-20, 2019.

[11] Q. Li und X. Ma, „A Meta-anamysis of the Effects of Computer Technology on School Students' Mathematics Learning,“ *Educ Psychol Rev,* pp. 215-243, 2010.

hpc.bw: A Supercomputer with Competence Platform for the Universities of the Federal Armed Forces

Philipp Neumann*, Johann Duffek, Jessica Kleinschmidt, Willi Leinen, Michael Breuer, Sabine Schmidt-Lauff, Andreas Fink
Helmut Schmidt Universität/ Universität der Bundeswehr Hamburg
Hamburg, Gemany
*philipp.neumann@hsu-hh.de

Matthias Mayr, Max Firmbach, Alexander Popp
Universität der Bundeswehr München
Munich, Germany

Axel Auweter
MEGWARE Computer Vertrieb und Service GmbH
Chemnitz, Germany

***Abstract* – Computational and data science have evolved as major pillars in basically all research disciplines. When it comes to efficiently solving compute- or data-intensive tasks such as numerical simulations, optimization problems or machine learning, researchers are, however, often confronted with several challenges which result in a sub-optimal research productivity. In our project hpc.bw, we strive to increase research productivity by providing high performance computing (HPC) systems, skills and support. In a highly interdisciplinary approach, we develop for this purpose a HPC competence platform at the Universities of the Federal Armed Forces. In this contribution, we detail our anticipated approach to disseminate and to transfer HPC knowledge across all disciplines. This includes a multiplicator program, performance engineering activities to boost discipline-specific software performance, hardware and software sustainability considerations and the development of a building block-based concept for HPC competences. All these activities integrate with the establishment of a container-based high performance computing center at Helmut-Schmidt-Universität and its supercomputer HSUper.**

Keyword* – *High performance computing, supercomputer, competence platform, performance engineering, education

NOMENCLATURE

CBRZ	Container-based high performance computing center[1]
HPC	High performance computing
HPCCP	HPC competence platform
HSU	Helmut-Schmidt-Universität/ Universität der Bundeswehr Hamburg
MPI	Message Passing Interface
OER	Open Educational Resources
UniBw M	Universität der Bundeswehr München

I. MOTIVATION

Computational and data science have evolved as major pillars in basically all research disciplines, complementing analytical and empirical or experimental studies. However, researchers are easily confronted with severe challenges when it comes to relying on computational methodologies and technology, especially when these turn out to be very compute- or data-intensive: computational resources might be lacking; if these resources are available, e.g. in the form of a supercomputer, it is not straight-forward to use them; programming skills that are necessary to optimize and parallelize programs to be used on such high performance computing (HPC) systems need to be acquired first, and this is often not included in discipline-specific under- or postgraduate programs; time to apply these skills to the actual research task and software might be scarce; etc. All these hurdles, in conjunction with the fact that HPC resources become more and more complex (heterogeneous architectures, often comprised of hybrid systems with CPUs and accelerators such as GPUs; growing memory hierarchies), induce a sub-optimal research productivity.

Goal and motivation of our dtec.bw-funded project *hpc.bw: Competence Platform for Software Efficiency and Supercomputing* is to decrease this gap. The aim is to strengthen innovative cross-site HPC research at the Universities of the Federal Armed Forces and to accelerate the transfer of HPC knowledge to a wide range of disciplines to

- sustainably strengthen research and development in the respective disciplines,
- promote interdisciplinary exchange between HPC-related problems,
- derive new research questions for HPC from discipline-specific problems and answer them, and
- establish a joint HPC competence platform for users within and outside the federal armed forces.

These activities are supported by the establishment of a container-based high performance computing center. An overview of project activities is provided in FIGURE 1.

In this contribution, we give an overview of project activities. First, we focus on our efforts to build an effective

[1] German: **C**ontainer-**b**asiertes HPC **R**echen**z**entrum

https://doi.org/10.24405/14569

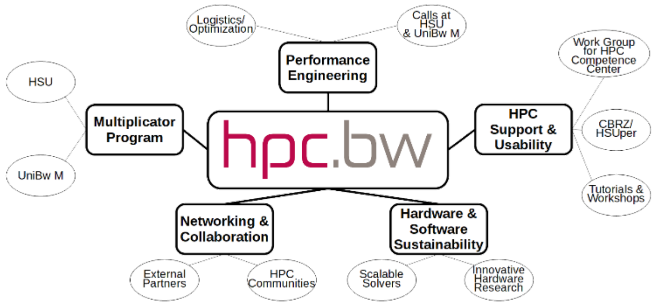


FIGURE 1: HPC.BW PROJECT OVERVIEW.

HPC community in Sec. II. Our approach to develop a HPC competence platform is explained in Sec. III. Hardware-aware HPC sustainability efforts with a focus on the establishment of a container-based high performance computing center including a PetaFLOP-capable supercomputer are detailed in Sec. IV. Research and support actions for HPC software are laid out in Sec. V. We close with an outlook to *hpc.bw* activities beyond the Universities of the Federal Armed Forces in Sec. VI and a conclusion in Sec. VII.

II. BUILDING A HPC COMMUNITY

Various measures have been taken to reach out to relevant user groups and to increase awareness for the project *hpc.bw* and its research and support actions, which shall in the long term feed into the formation of an active, highly interdisciplinary HPC community.

A. Multiplicator Program

An essential point from the very beginning of the project was the involvement of all potential HPC user groups. The term “user group” is interpreted in the widest sense: users may come from any discipline (social sciences, natural sciences, economics, engineering, …), they might already have HPC experiences at various levels, or they might be beginners, recognizing the potential that high performance computing may provide to their research field. To reach out to these groups in a top-down approach, a multiplicator program has been launched. One multiplicator of every involved organizational unit is a member of the project consortium. Due to current HPC demands, UniBw M and every department at HSU act as one organizational unit each. The multiplicators spread news on the project in the relevant university boards (e.g., information on *hpc.bw* newsletters) and are further involved in decision-making processes such as the evaluation of performance engineering project proposals, cf. Sec. V.A.

B. Newsletters

Complementing the multiplicator program, a newsletter series has been launched in the beginning of 2022 to disseminate *hpc.bw*-related activities to a wider audience [1], [2]. The quarterly newsletters are made available on the current project website[2] and on the portal OpenHSU[3].

C. Meeting the Community: Seminar Computation & Data

Besides, *hpc.bw* actively contributed to bringing together researchers that work in the fields of computational and data science in the widest sense. A monthly seminar series “Computation & Data” was launched in March 2022, where in each session 1-2 researchers from the Universities of the Federal Armed Forces, but also invited speakers and collaboration partners, present their work.

III. TOWARDS A HPC COMPETENCE PLATFORM

A specific aim in the overall *hpc.bw* project is to initiate, expand and establish the transfer of HPC knowledge via a joint HPC competence platform (HPCCP) for users within and outside the federal armed forces. The HPCCP represents an open concept with newly created and systematically organized learning resources for the use of HPC systems and various target groups, cf. Sec. II.A. The implementation of the adult education activities can be digital, on-site or hybrid. The learning content will be open access as OER where possible and appropriate.

By providing learning opportunities and adult education concepts, an interdisciplinary contribution will be realized, leading to the development of new areas of knowledge and research in HPC. The following examples are working areas of the HPCCP:

- Learning and networking opportunities for different user groups (e.g., seminar series, workshops, tool talks, poster presentations).
- Teaching/learning material for different target groups (e.g., wikis, online tutorials, tool talk)
- Illustrative material (also digitally prepared) for low-threshold, non-specialist access to various service areas of HPC (e.g., basic knowledge, application fields, implementation examples, benefit analyses)
- Development of digital OER
- Establishing a web platform for the provision of developed materials (e.g., reports, online tools, workshop concepts) for HPC competences
- Continuous improvement through piloting (e.g., feedback, evaluations, needs assessments)
- Continuity through thematic updates, adaptation to demand and collaborative further developments

IV. HSUPER AND HARDWARE SUSTAINABILITY

A. Container-based High Performance Computing Center and HPC cluster HSUper

At the core of high performance computing lies the use of supercomputers. The “from-scratch” design, provision and commissioning of these computational resources requires various considerations. At its heart, the design of the supercomputer must enable optimal performance for the

[2] https://www.hsu-hh.de/wb/hpc-bw

[3] https://openhsu.ub.hsu-hh.de/

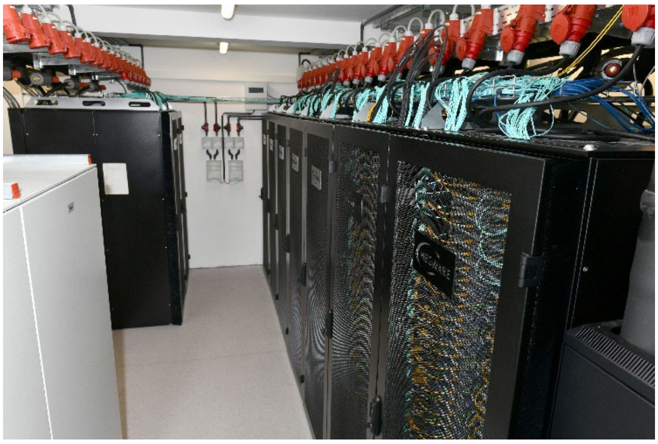


FIGURE 2: CBRZ (TOP; FOUR CONTAINERS TO THE LOWER RIGHT, FRONT SIDE OF THE CONTAINER-BASED BUILDING) WITH HPC CLUSTER HSUPER (BOTTOM). PHOTOS COURTESY BY U. SCHRÖDER, HSU.

anticipated compute loads, which are, in this case, numerical simulations, but also data analysis and machine learning tasks. The massive power consumption of HPC systems results in the dissipation of energy in form of heat. Using this dissipated heat is highly desirable, so that the system is operated in an environment-friendly way ("green computing"). Infrastructural prerequisites need to be satisfied: besides aforementioned massive power supply, enough space for the compute system and its infrastructure (e.g., cooling system) must be available, which is a challenge for smaller universities and holds in particular for HSU, given the current, enormous build-ups on campus. Finally, a heterogeneous user base with foci on, amongst others, computational fluid dynamics simulations, material science investigations and machine learning, requests different kinds of compute systems.

Under these constraints, the concept of a container-based HPC center (CBRZ) including supercomputer HSUper was developed, cf. FIGURE 2. It was subsequently realized by MEGWARE Computer Vertrieb und Service GmbH. Four 20 foot containers, integrated in a container-assembled building, host the supercomputer, which currently consists of nine compute racks. To allow an as-compact-as-possible hosting of processors in the racks and to improve the energy-efficiency of the system, a liquid-cooling approach has been followed for most components of HSUper. The cooling system has been designed for the highest possible density and efficiency. Depending on the operational mode and the season, this allows to either emit the generated heat via roof-mounted fans or to reuse the heat for the heating system of the container building in the future.

The supercomputer HSUper consists of three partitions of compute nodes. The biggest partition consists of 571 dual socket Intel Icelake compute nodes, each node equipped with 256 GB RAM and 2x36 compute cores. This partition allows the execution of classical x86-based software (such as most commercial simulation software in science and engineering). A second partition comprises five nodes identical to the ones of the first partition, but each featuring 1 TB RAM, to handle extremely data-intensive workloads. A third partition comprises five nodes identical to the ones of the first partition, but each node featuring two additional NVIDIA A100 graphics cards. These nodes are optimal for, amongst others, machine learning workloads. All compute nodes of HSUper are interconnected by a low-latency HDR100 InfiniBand network. The computational components are complemented by two file systems: a 1PB-sized BeeGFS-based parallel file system for most use cases and a 1PB-sized Ceph storage, which shall be particularly leveraged in combination with a digital tomography center for materials science.

HSUper has entered the TOP500 list of the fastest supercomputers in the world in June 2022, ranked 339 with a Linpack performance of 2.13 PFLOPS[4] [3]. It is further ranked 70 in the Green500 list, which measures the computational performance per consumed Watt. After a beta user phase for HSUper since spring 2022 the system is in productive operation starting late summer 2022.

Computational fluid dynamics applications are one of the main use cases of HPC resources especially when transitional or turbulent flows and multiphysics simulations such fluid-structure interactions are the objective. Therefore, it is not surprising that fluid mechanics was one of the first application fields of the new system HSUper. FIGURE 3 shows an example of some basic research application on the transition from a laminar to a turbulent flow in a pipe at Reynolds number Re = 15,000 [4]. Originally, the flow is laminar as can be seen by the straight line of the tracer particles. Triggered by a wall-mounted ring-type obstacle, small disturbances develop at about the middle of the pipe. Further downstream these are increasing finally, leading to transition. That becomes obvious in FIGURE 3 from the chaotic mixing of the tracer particles which is typical for turbulent flows. The background of such direct numerical simulations is an in-house CFD solver which is parallelized by domain decomposition relying on the message-passing interface (MPI). Before running extensive application cases, we investigated the performance of the new system for varying numbers of compute nodes and cores. The test case chosen is based on 210 MPI processes which are split up in different manners. The extreme cases are that solely one core per node or all physically available 72 cores are applied. FIGURE 4 depicts the ratio of the wall-clock time of each case to the one core-per-node case using 210 nodes. Up to 8 cores per node, the ratio of the wall-clock times stays close to unity. However, for 12 and more cores per node a saturation of the memory bandwidth of the nodes sets in leading to significantly longer wall-clock times up to a factor of 3.8 in case all cores of the Intel Icelake compute nodes are used. Thus, a

[4] 1 PFLOPS=1 PetaFLOP/s=10^{15} **Fl**oating Point **Op**erations per **S**econd

compromise between required nodes and acceptable wall-clock times has to be found in practice.

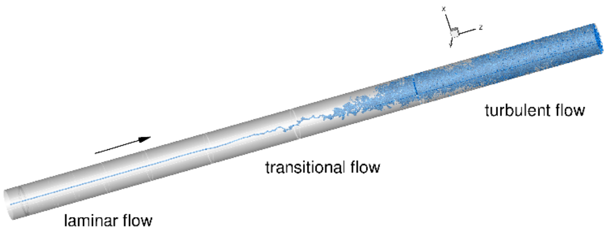


FIGURE 2: LAMINAR-TURBULENT TRANSITION IN A PIPEFLOW [4].

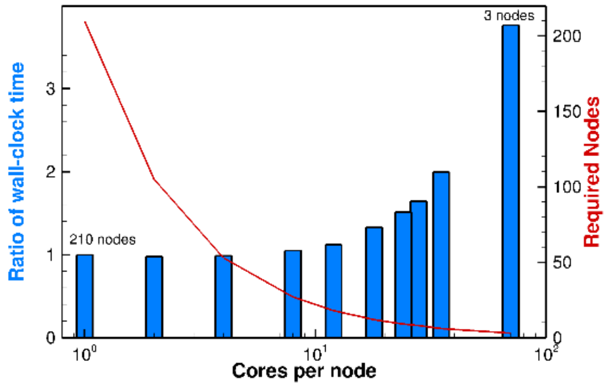


FIGURE 4: RESULTS OF PERFORMANCE TESTS ON HSUPER FOR THE COMPUTATIONAL FLUID DYNAMICS SHOW CASE.

B. Hardware Sustainability

HPC hardware develops rapidly, with novel attractive hardware released every year. It is essential to keep up with these hardware trends for strategic planning of the next-generation supercomputer. This also means that an understanding of the compute capabilities of potentially relevant novel hardware for user-specific application cases needs to be acquired and, based on this understanding, judge upon the hardware line's relevance in future procurements.

Against this background, selected novel HPC hardware is procured at small scale, installed and investigated in terms of user-defined benchmark cases by the project consortium of *hpc.bw*. Until now, two systems have been investigated:

- 4-node AMD EPYC[5] 7763 system, each node with 64 cores running at 2.25 GHz and with 256 GB RAM
- 8-node ARM-based Fujitsu A64FX[6] system, each node with 48 cores running at 2 GHz and with 32 GB high bandwidth memory

FIGURE 5 exemplarily shows scalability results for both pieces of hardware for a coupled flow simulation.

C. Outlook: Computing for Everyone – Interactive Scientific Computing Cloud

Supercomputers are efficient means for large-scale computational tasks. However, their use is more challenging and often requires advanced command line and shell scripting skills, use of HPC schedulers, and, to some extent, parallel architectures.

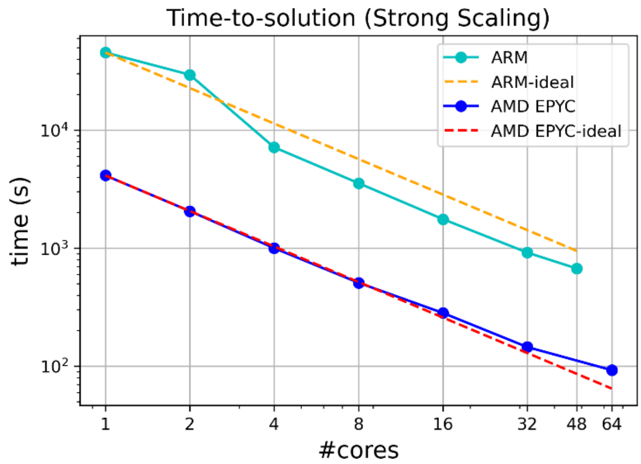


FIGURE 5: SCALABILITY, I.E. RUNTIME DEPENDING ON THE NUMBER OF COMPUTE CORES, OF A COUPLED MOLECULAR DYNAMICS-COMPUTATIONAL FLUID DYNAMICS APPLICATION, INVOKING A SIMPLE LATTICE BOLTZMANN FLOW SOLVER AND THE HIGHLY EFFICIENT MOLECULAR DYNAMICS SOFTWARE LS1 MARDYN/AUTOPAS [5]. COUPLING IS ACCOMPLISHED USING THE MACRO-MICRO COUPLING TOOL [6]. THE CONSIDERED HARDWARE SYSTEMS ARE ARM A64FX AND AMD EPYC 7763. ON BOTH PIECES OF HARDWARE, CLOSE-TO-OPTIMAL SCALABILITY IS OBSERVED, FOLLOWING THE IDEAL SCALING CURVES. OPTIMIZATION OF THE SOFTWARE FOR THE ARM ARCHITECTURE IS ONGOING WORK.

This also renders their use for (non-HPC) teaching unattractive. An interactive scientific computing on-premise cloud is planned

- to support users that have workstation-level (or slightly beyond) computational and data tasks,
- as platform for teaching simulation- and data-driven methods and their application fields,
- to simplify collaboration with other groups.

hpc.bw is supported in this endeavor by algorithmica technologies GmbH.

V. SOFTWARE EFFICIENCY AND SUSTAINABILITY

A. Performance Engineering Projects

At the core of *hpc.bw* lies the approach to boost research productivity by optimizing user-specific software on the one side and to derive new HPC research questions from this optimization process on the other side. This approach has been realized in terms of regular project calls for performance engineering projects. Every member of the Universities of the Federal Armed Forces can apply with his/ her own software. Projects are meant to last for a maximum of 12 months, but must not exceed six person months in total on HPC side for the optimization procedure. Submitted project proposals are reviewed by the *hpc.bw* project coordinator and the *hpc.bw* multiplicators, cf. Sec. II.A, to account for the interdisciplinary character of the projects.

[5] 5 out of the 10 fastest supercomputers (TOP500 list) leverage AMD EPYC processors at node-level, as of June 2022

[6] The supercomputer Fugaku, ranked 2 in the TOP500 list as of June 2022, leverages a similar node-level ARM technology

TABLE I: OVERVIEW OF PERFORMANCE ENGINEERING PROJECTS SUPPORTED BY HPC.BW IN 2022

Title	Research Field, University
benEFIT – Numerical simulation of non-destructive testing in concrete	Engineering Materials and Building Preservation, HSU
Enabling high-throughput studies of reactive materials	Computational Material Design, HSU
Monte Carlo simulations of real fluids	Thermodynamics, HSU
Optimization of an IGA code in Matlab for parallel computing	Mechanics and Statics, UniBw M

The first call was closed in February 2022. Four out of eight submissions have been selected for *hpc.bw* performance engineering support, cf. TABLE I. First results have been achieved in the project "Monte Carlo simulations of real fluids". Data buffering and SIMD pragmas for improved vectorization resulted in a speedup of 2 (i.e., halving the overall execution time) for examined use cases, cf. FIGURE 6. Upcoming calls are planned on an annual basis, with the next call anticipated for winter 2022/23.

B. *Supporting Software Sustainability Efforts*

To efficiently develop and maintain research and application codes and to allow developers to focus on their specific domain expertise (and to not have to re-write basic algorithms from scratch), today's software systems crucially rely on the existence of optimized and mature building blocks to be (re-)used by domain scientists. Within *hpc.bw*, we strive to provide such building blocks as enabling technology for other researchers and their HPC codes.

To support the simulation of coupled multi-physics phenomena in various disciplines, the *hpc.bw* project team at UniBw M develops and maintains a variety of multi-level block preconditioning methods to efficiently solve large linear systems of equations arising from the discretization of coupled problems. As illustrated in FIGURE 7, multi-level methods employ a hierarchy of coarse representations of the original fine level problem and reconstruct the fine level solution from information from the coarse levels [7]. This allows to solve problems with several million unknowns accurately and efficiently, while also obtaining *parallel scalability*, i.e. an optimal use of supercomputing hardware. We contribute our algorithms as open-source implementations to the MueLu package[7] of the Trilinos Project[8], such that they are elegantly embedded into a widely used software ecosystem for HPC and can be used by any researcher worldwide. As exemplary application, the *hpc.bw* team at UniBw M targets the embedding of thin fibers into solid bodies, as e.g. in reinforced concrete or composite materials.

To further increase the outreach into the scientific community, *hpc.bw* organizes the *European Trilinos User Group (EuroTUG) Meeting* to be held in Munich in 2022 and in Hamburg in 2024. The EuroTUG meeting series offers a platform for Europe-based users and developers of the Trilinos Project to learn about recent developments in Trilinos, report on their use cases and experiences with Trilinos, interact with the Trilinos leadership and core developers, and form a European network of Trilinos users and developers.

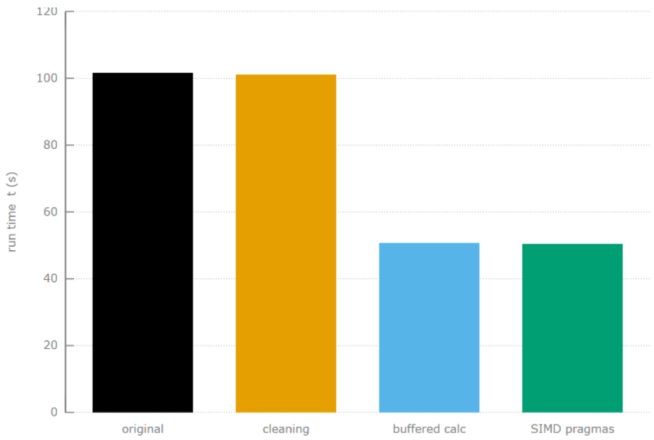


FIGURE 6: PRELIMINARY PERFORMANCE RESULTS FOR MONTE-CARLO SIMULATION AFTER SUBSEQUENT OPTIMIZATION STEPS FOR A TWO-BODY INTERACTION PROBLEM. ORIGINAL: RUNTIME BEFORE OPTIMIZATIONS. CLEANING: CODE REFACTORING TO SIMPLIFY PERFORMANCE ENGINEERING. BUFFERED CALC: BUFFERING OF PARTICLE DISTANCES TO ENABLE AUTO-VECTORIZATION. SIMD PRAGMAS: USE OF SIMD PRAGMAS TO LEVERAGE VECTORIZATION PROPERTIES OF X86 PROCESSORS.

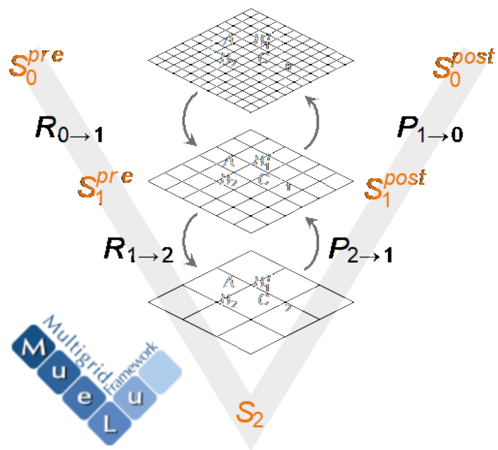


FIGURE 7: MULTI-LEVEL BLOCK PRECONDITIONING IN MUELU.

VI. OUTLOOK: HPC FOR LOGISTICS

While HPC is already well established in research and development fields such as engineering and science, there is still much room for solving optimization problems in business administration and economics [8]. Considering the application area of logistics, there are a multitude of diverse planning problems of high relevance notably with respect to economic efficiency and ecological sustainability (e.g., various kinds of scheduling and vehicle routing problems). Even simplified models of such problems from practice are often NP-hard,

[7] https://trilinos.github.io/muelu.html

[8] https://trilinos.github.io/

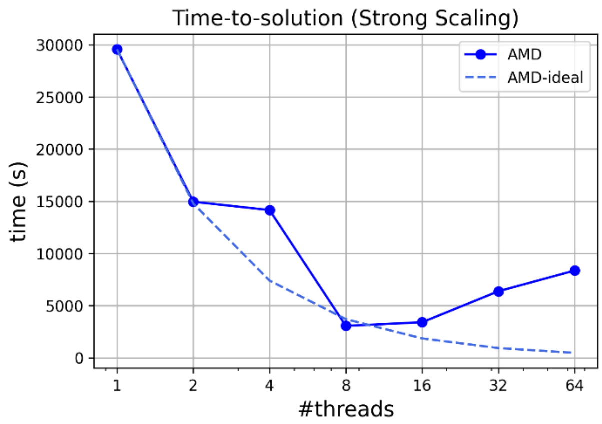


FIGURE 8: RUNTIME IN SECONDS OVER NUMBER OF USED COMPUTE CORES, I.E. USED THREADS TO COMPUTE AN OPTIMAL SOLUTION OF THE TIME-DEPENDENT TRAVELING SALESMAN PROBLEM TA061 FROM [9] WITH N=100 NODES USING IBM ILOG CPLEX OPTIMIZATION STUDIO, VERSION 22.1.0, WITH DEFAULT SETTINGS ON THE AMD SYSTEM

which means that to date many problems cannot be solved exactly even for relatively small problem sizes with ordinary computing power. Therefore, exploiting HPC power may extend the possibilities for tackling such computationally hard combinatorial optimization problems to a certain degree (regarding exactly solving somewhat larger problems or improving the approximation quality).

However, existing optimization methods often have a sequential flow logic at their core (with limited data-parallel concurrency), which is why such algorithms often must be adapted or even newly designed and implemented for HPC architectures with parallelization in mind [10]. In particular, hybrid optimization methods are being developed and investigated regarding parallelization (including mixed-integer mathematical optimization, constraint programming methods and metaheuristics/local search methods).

In a first step, we are investigating how available mixed-integer mathematical optimization solvers are already able to exploit parallel computing power of the shelf (considering both shared memory multi-core parallelization as well as distributed computing). FIGURE 8 shows first performance results for the time-dependent traveling salesman problem.

With the goal in mind to establish a joint HPC competence platform for users within, but also outside the federal armed forces, *hpc.bw* strives to collaborate with companies on HPC-related topics. The first collaboration has been initialized with Opheo Solutions GmbH, who develop a transport management software including an optimizer for tour planning. In the project, HPC experts from *hpc.bw* team up with the software developers of Opheo to improve the efficiency of the optimization process, researching parallel algorithms and efficient implementations thereof.

VII. CONCLUSION

With the project *hpc.bw*, the Universities of the Federal Armed Forces pave the way towards a competence platform around the wide field of high performance computing.

Establishing the container-based HPC center including the supercomputer HSUper was a challenge, as it required intense interactions of HPC experts, hardware vendor (including sub-contractors), infrastructure officers and architect. HSUper appears to be a very promising machine for the Universities of the Federal Armed Forces, and we look forward to exploring its performance and benefits for our HPC community.

While various view points from multiple user profiles have been taken into consideration to design the concept for the HPCCP, its actual implementation is the next step, which is planned for the upcoming months.

ACKNOWLEDGEMENT

The work described in this contribution has been funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project *hpc.bw: Competence Platform for Software Efficiency and Supercomputing*].

REFERENCES

[1] P. Neumann and J. Kleinschmidt, "hpc.bw Newsletter 01/2022," Hamburg, 2022.

[2] P. Neumann and J. Kleinschmidt, "hpc.bw Newsletter 02/2022," Hamburg, 2022.

[3] E. Strohmaier, J. Dongarra, H. Simon and M. Meuer, "TOP500," June 2022. [Online]. Available: https://www.top500.org/lists/top500/list/2022/06/?page=4. [Accessed 27 July 2022].

[4] F. Durst, M. Breuer, B. Ünsal and K. Haddad, "Laminar-to-turbulent transition of pipe flows triggered by wall-mounted ring-type obstacles," *J. of Turbulence,* vol. 23, no. 7, pp. 382-404, 2022.

[5] S. Seckler, F. Gratl, M. Heinen, J. Vrabec, H.-J. Bungartz and P. Neumann, "AutoPas in ls1 mardyn: Massively Parallel Particle Simulations with Node-Level Auto-Tuning," *Journal of Computational Science,* vol. 50, p. 101296, 2021.

[6] P. Neumann, H. Flohr, R. Arora, P. Jarmatz, N. Tchipev and H.-J. Bungartz, "MaMiCo: Software design for parallel molecular-continuum flow simulations," *Computer Physics Communications,* vol. 200, pp. 324-335, 2016.

[7] A. Brandt, "Multi-Level Adaptive Solutions to Boundary Value Problems," vol. 88, no. 138, pp. 333-390, 1977.

[8] G. Schryen, N. Kliewer and A. Fink, "High Performance Business Computing," *Business & Information Systems Engineering,* vol. 62, pp. 1-3, 2020.

[9] A. Fink and S. Voß, "Solving the continuous flow-shop scheduling problem by metaheuristics," *European Journal of Operational Research,* vol. 151, no. 2, pp. 400-414, 2003.

[10] G. Schryen, "Parallel computational optimization in operations research: A new integrative framework, literature review and research directions," *European Journal of Operational Research,* vol. 287, pp. 1-18, 2020.

Das dtec.bw-Forschungsprojekt „Kompetenzen für die digitale Arbeitswelt (KoDiA) – Ertüchtigung zur Digitalisierung“ als Beispiel kontextualisierter Forschung

Andrea Neusius, Manuel Schulz
Zentrum für technologiegestützte Bildung
Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg
Hamburg, Deutschland
neusius@hsu-hh.de

***Kurzfassung* – Im Forschungsprojekt “Kompetenzen für die digitale Arbeitswelt – Ertüchtigung zur Digitalisierung“ geht es darum, Menschen dabei zu unterstützen, die fortschreitende Digitalisierung in allen Lebensbereichen aktiv, mündig und verantwortungsvoll mit zu gestalten. Der Forschungsansatz reicht somit über eine bloße Anpassung der Menschen an die Anforderungen der Technik hinaus.**

Im Fokus der Forschung steht die Idee der Gerechtigkeit im Verständnis von, Bildungsgerechtigkeit, Adressat:innengerechtigkeit und Teilhabegerechtigkeit.

Mit diesem Fokus umfasst das Projekt KoDiA insgesamt drei Arbeitspakete:

Das Arbeitspaket „Bildung für die digitale Arbeitswelt“ zielt auf die Ertüchtigung des Subjekts. Im Vordergrund steht die Frage, wie Bildung dazu beitragen kann, dass Bürger:innen durch mündige Teilhabe Digitalisierung mitgestalten können. Im Kern geht es dabei um das Austarieren einer eigenen Positionierung zwischen Anpassung und Eigensinn, zwischen Vertrauen und Misstrauen.

Diese Positionierung basiert auf Informationen. Angesichts der Komplexität unserer heutigen Lebenswelt kommt wissenschaftlich validierter Information dabei eine besondere Rolle und uns Wissenschaftler:innen eine besondere Verantwortung zu.

Darum geht es im Arbeitspaket „Innovative Kooperationen“. Wir schlagen hierfür das Konzept einer „Öffentlichen Wissenschaft“ (in Anlehnung an den Ansatz einer „Öffentlichen Soziologie“, wie u.a. von Aulenbacher, Burawoy, Dörre und Sittel 2017 formuliert [1]) vor: Das Konzept der Öffentlichen Wissenschaft zielt darauf ab, den Dialog zwischen Wissenschaftler*innen und Öffentlichkeit auf Augenhöhe zu ermöglichen. Auf diese Weise können Theorien, Erkenntnisse und Forschungsergebnisse für die Öffentlichkeit nutzbar werden. Gleichzeitig erfahren Wissenschaftler:innen, welche konkreten Herausforderungen als Fragestellungen für Forschung und Theoriebildung untersucht werden können, um konkrete Probleme, die auch in einer nicht-wissenschaftlichen Öffentlichkeit als solche erachtet werden, forschend zu lösen.

Wissenschaft kann in diesem Verständnis einen Referenzrahmen für das Subjekt zur eigenen Positionierung zwischen Anpassung und Widerstand bieten.

Dabei haben wir während der Coronapandemie erlebt, wie riskant die Verlagerung wissenschaftlichen inter- und sogar intradisziplinären Diskurses in die Öffentlichkeit zum Beispiel in Talkshows sein kann. Schnell entsteht der Eindruck, dass Begriffe, Methoden und daraus resultierende Erkenntnisse Ansichtssache sind und der je individuellen „Meinung“ der einzelnen Wissenschaftler:innen unterliegen.

Wir sehen eine wesentliche Ursache für dieses Phänomen in der weitreichenden Zergliederung der Wissenschaftsdisziplinen und -domänen, die zu je spezifischen Definitionen, Methoden und Interpretationslogiken führen können. Im Arbeitspaket „Aufbau eines interdisziplinären Forschungsnetzwerks“ streben wir deshalb eine Art Stakeholder Balancing an, um solche Widersprüche dort, wo dies durch Dialog und die Fachgrenzen überschreitenden Diskurs möglich ist, abzubauen.

Dabei verstehen wir Forschung im Rahmen von KoDiA als kontextualisierte Forschung. Damit verbinden wir den Anspruch, Theorien, wissenschaftliche Konzepte und Idealvorstellungen von Bildung dort zu erforschen, wo Bildung stattfindet und unter den realen Rahmenbedingungen beispielsweise von beruflicher Bildung an Berufsschulen.

Kontextualisierte Forschung ist also Forschung, die in einen realen Untersuchungs- und Implementierungskontext eingebettet ist. Diese Art der Forschung zeichnet sich dadurch aus, dass am Forschungsprozess nicht nur Akteur:innen der Wissenschaft beteiligt sind, sondern auch die Praktiker:innen des jeweiligen Gegenstandsfeldes.

Im Forschungsprozess erfordert diese Vorgehensweise permanent eine gemeinsame Auseinandersetzung mit dem Forschungsgegenstand, miteinander und auch mit den Rahmenbedingungen, die wir im institutionellen Kontext der Forschung vorfinden.

Im vorliegenden Beitrag werden wir anhand ausgewählter Beispiele unser Forschungsprojekt und bisher gewonnene Erkenntnisse vorstellen.

https://doi.org/10.24405/14570

I. Einordnung und Rahmenbedingungen

Der Soziologe Dirk Baecker (2017) bewertet in Anlehnung an Niklas Luhmann die fortschreitende weltweite Digitalisierung als ähnlich großen Entwicklungsschritt für die Menschheit, wie die Entwicklung der Sprache, der Schrift und des Buchdrucks. Alle diese Entwicklungsschritte der Menschheit haben Überschussfunktionalitäten (Baecker nennt sie in der Luhmann'schen Terminologie „Überschusssinn“ [2, p. 5] mit sich gebracht, die seit Beginn der jeweiligen Entwicklung nicht einmal im Ansatz absehbar waren.

Unter diesem Rahmen fokussiert das Forschungsprojekt “Kompetenzen für die digitale Arbeitswelt – Ertüchtigung zur Digitalisierung“ auf die Weiterentwicklung und Sicherstellung einer fairen Interaktion der Menschen in einer demokratischen Gesellschaft. Im Kern geht es darum, unter den Bedingungen einer fortschreitenden Digitalisierung und deren noch nicht absehbaren Begleitentwicklungen und -erscheinungen weiterhin den Menschen die Möglichkeit einzuräumen und sie darauf vorzubereiten ihre Interessen und Bedürfnisse aktiv, mündig und verantwortungsvoll einzubringen und Digitalisierung mit zu gestalten.

Somit reicht der Forschungsansatz über eine bloße Anpassung der Menschen an die Anforderungen der Technik hinaus. Um diese weit reichenden Forschungsziele zu operationalisieren, fokussieren wir besonders Gerechtigkeit in einem Verständnis von Bildungsgerechtigkeit, Adressatengerechtigkeit und Teilhabegerechtigkeit.

Das Forschungsprojekt wird finanziert aus Mitteln des im Rahmen des Konjunkturpakets der Bundesregierung „Corona-Folgen bekämpfen, Wohlstand sichern, Zukunftsfähigkeit stärken“ an den beiden Universitäten der Bundeswehr neu aufgestellten „Zentrums für Digitalisierungs- und Technologieforschung (dtec.bw)“ [3]. Ziel des dtec.bw ist es, einen Beitrag zu leisten zu Gewinn und Erhalt der digitalen Souveränität Deutschlands. Hier bieten die Universitäten der Bundeswehr ein sicheres Umfeld für innovative und interdisziplinäre Forschung, an der Wissenschaft, Wirtschaft, Verwaltung und Gesellschaft teilhaben können. Die universitäre Digitalisierungs- und Technologieforschung der Bundeswehr soll auf diese Weise gestärkt werden und digitale und technologische Innovationen, die in diesem Kontext entstehen, sollen für die öffentliche und private Nutzung verfügbar werden. Ein weiteres wichtiges Ziel ist es, ein offenes und allgemein zugängliches Forum, auch für den Dialog mit der Gesellschaft zu Technologiefragen zu schaffen [4].

Die für den Anteil des dtec.bw an der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg bereitgestellten Haushaltsmittel im Wettbewerb vergeben. Die eingereichten Forschungsanträge wurden durch eine wissenschaftliche Gutachterkommission geprüft und über die Vergabe der Haushaltsmittel an die Forschungsvorhaben entschieden. In insgesamt vier „Dachprojekten“, von denen eines – namensgleich mit unserem Einzelprojekt – „Kompetenzen für die digitale Arbeitswelt (KoDiA)“ benannt ist, wird zurzeit in 45 Einzelprojekten geforscht.

Im Folgenden möchten wir unser Einzelprojekt „Kompetenzen für die digitale Arbeitswelt (KoDiA) – Ertüchtigung zur Digitalisierung“ ausführlicher vorstellen und unseren Forschungsansatz einer kontextualisierten Forschung erläutern.

II. Das Forschungsprojekt KoDiA im Überblick

Im Fokus des Forschungsprojekts steht die Idee der Gerechtigkeit im Verständnis von Bildungsgerechtigkeit, Adressat:innengerechtigkeit und Teilhabegerechtigkeit unter den Bedingungen einer fortschreitenden Digitalisierung unserer Arbeits- und Lebenswelt. Mit unserem Forschungsansatz schließen wir an die von Dirk Baecker 2017 formulierte „Frage nach dem Menschen und seiner Gesellschaft“, die er als notwendig erachtet, um „die Einführung digitaler Produktionsverfahren, neuer Steuerungstechnologien, elektronischer Überwachungstechniken, konnektiver Algorithmen, ungeordneter Datenspeicher, der Internetrecherche, der Blogosphäre, der Big-Data-Versprechen usw. zu verstehen“ [2, p. 4], an. Baecker erachtet die Digitalisierung als eine Medienepoche, die im Luhmann'schen Sinne „Überschusssinn“ erzeugt und beschreibt sie als eine Entwicklungsstufe in der Evolution von Verbreitungsmedien der Gesellschaft, zu denen er die Sprache (Verbreitungsmedium der tribalen Gesellschaft), die Schrift (Verbreitungsmedium der Antike), den Buchdruck (Verbreitungsmedium der modernen Gesellschaft) zählt [2, p. 5]. Im Kontext dieser „archäologischen“ Perspektive stellt die Digitalisierung ihre Gesellschaft in die Bedrohung ihrer bisherigen Ordnung und vor die Herausforderung der Etablierung einer neuen Ordnung (denn die Ablehnung eines neuen Verbreitungsmediums kann schon deshalb nicht gelingen, da diese bereits selbst „eine Form der Entdeckung möglichen Nutzens“ ist [2, p. 7]. Auch aus dieser Perspektive ist es deshalb entscheidend, die Voraussetzungen für die Etablierung einer neuen Ordnung unter den Bedingungen des neuen Verbreitungsmediums elektronischer / digitaler Kommunikation zu erforschen und dafür auf der Ebene der Gesellschaft und der diese tragenden Subjekte zu beginnen.

Mit diesem Fokus umfasst das Projekt KoDiA insgesamt drei Arbeitspakete [5]:

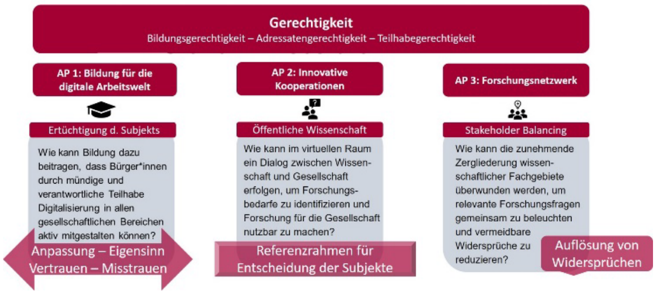


Abbildung 1: Übersicht Arbeitspakete KoDiA-Projekt.

A. *Arbeitspakete*

1) *Arbeitspaket 1 „Bildung für die digitale Arbeitswelt“*

Das Arbeitspaket 1 „Bildung für die digitale Arbeitswelt“ zielt auf die Ertüchtigung des Subjekts. Im Vordergrund steht die Frage, wie Bildung dazu beitragen kann, die Bürger:innen zu ermuntern und zu befähigen, sich durch mündige Teilhabe in die Mitgestaltung der Digitalisierung einzubringen. Im Kern geht es dabei um das immer wieder erforderliche Austarieren einer eigenen Positionierung zwischen Anpassung und Eigensinn und der Frage, welchen Instanzen und Informationen wir vertrauen können und welchen wir eher misstrauen sollten.

Am Beispiel ausgewählter Bildungseinrichtungen und Bildungsgänge werden didaktische Konzepte entwickelt und erprobt, um Menschen Möglichkeiten der Entwicklung von Eigensinn und Durchsetzung dieses Eigensinns, aber auch zur demokratischen Konsensfindung und damit Anpassung an kompromisshafte oder konsensuale Entscheidungen zu erschließen.

Dabei spielt der Rückgriff auf Informationen und deren Bewertung als Grundlage für Diskussion und Entscheidung eine zentrale Rolle. Angesichts der Komplexität unserer heutigen Lebenswelt kommt wissenschaftlich validierter Information dabei eine besondere Bedeutung und Wissenschaftler:innen eine besondere Verantwortung zu.

2) Arbeitspaket 2 "Innovative Kooperationen

Darum geht es im Arbeitspaket 2 „Innovative Kooperationen". Wir schlagen hierfür das Konzept einer „Öffentlichen Wissenschaft" (in Anlehnung an den Ansatz einer „Öffentlichen Soziologie", [1]) vor: Das Konzept der Öffentlichen Wissenschaft zielt darauf ab, den Dialog zwischen Wissenschaftler*innen und Öffentlichkeit auf Augenhöhe zu ermöglichen. Auf diese Weise können Theorien, Erkenntnisse und Forschungsergebnisse für die Öffentlichkeit nutzbar werden. Gleichzeitig erfahren Wissenschaftler:innen, welche konkreten Herausforderungen als Fragestellungen für Forschung und Theoriebildung untersucht werden können, um konkrete Probleme, die auch in einer nicht-wissenschaftlichen Öffentlichkeit als solche erachtet werden, forschend zu lösen [6].

Wissenschaft kann in diesem Verständnis einen Referenzrahmen für das Subjekt zur eigenen Positionierung zwischen Anpassung und Widerstand bieten.

Dabei haben wir während der Coronapandemie erlebt, wie riskant die Verlagerung wissenschaftlichen inter- und sogar intradisziplinären Diskurses in die Öffentlichkeit zum Beispiel in Talkshows sein kann. Schnell entsteht der Eindruck, dass Begriffe, Methoden und daraus resultierende Erkenntnisse Ansichtssache sind und der je individuellen „Meinung" der einzelnen Wissenschaftler:innen unterliegen.

3) Arbeitspaket 3 "Querschnittliches Forschungsnetzwerk"

Wir sehen eine wesentliche Ursache für dieses Phänomen in der weitreichenden Zergliederung der Wissenschaftsdisziplinen und -domänen, die zu je spezifischen Definitionen, Methoden und Interpretationslogiken führen können. Im **Arbeitspaket 3 „Aufbau eines interdisziplinären Forschungsnetzwerks"** streben wir deshalb eine Art Stakeholder Balancing an, um solche Widersprüche dort, wo dies durch Dialog und die Fachgrenzen überschreitenden Diskurs möglich ist, abzubauen.

B. Zum Verständnis kontextualisierter Forschung

Dabei verstehen wir Forschung im Rahmen von KoDiA als kontextualisierte Forschung. Damit verbinden wir den Anspruch, Theorien, wissenschaftliche Konzepte und Idealvorstellungen von Bildung dort zu erforschen, wo Bildung stattfindet und unter den realen Rahmenbedingungen beispielsweise von beruflicher Bildung an Berufsschulen.

Kontextualisierte Forschung ist also Forschung, die in einen realen Untersuchungs- und Implementierungskontext eingebettet ist. Diese Art der Forschung zeichnet sich dadurch aus, dass am Forschungsprozess nicht nur Akteur:innen der Wissenschaft beteiligt sind, sondern auch die Praktiker:innen des jeweiligen Gegenstandsfeldes.

Im Forschungsprozess erfordert diese Vorgehensweise permanent eine gemeinsame Auseinandersetzung mit dem Forschungsgegenstand, miteinander und auch mit den Rahmenbedingungen, die wir im institutionellen Kontext der Forschung vorfinden. Diese gemeinsame Auseinandersetzung verstehen wir im Sinne eines Stakeholder Balancing. Wir verwenden den Begriff des „Stakeholder Balancing", weil wir in vielen vorangegangenen Forschungsprojekten gelernt haben, dass Stakeholderinteressen sich im Verlauf des gemeinsamen Prozesses unterschiedlich entwickeln können und ein Interessenausgleich eine kontinuierliche, jedoch nicht lineare (und damit vorhersehbare) Aufgabe für das Management eines kontextualisierten Forschungsprojektes darstellt.

Wir erinnern an dieser Stelle an die Lippmann-Dewey-Debatte, in der Walter Lippmann als Vordenker des Neoliberalismus argumentierte, dass das Ideal des Subjekts als mündiger:m Bürger:in eine Illusion sei und öffentliche Meinung durch Medien (er prägte hierfür den Begriff „gatekeeper") gelenkt sei. Information erreiche die Bürger:innen demnach immer gefiltert durch mehrere Selektionsprozesse. Funktional sei Journalismus im Sinne von Informationsbereitstellung dann, wenn dadurch eine weitgehend homogene öffentliche Meinung entstehe, die die jeweils Regierenden stütze [7, p. 108 f.]. Demgegenüber positioniert sich John Dewey als Verfechter der mündigen Bürger:innen als notwendige Bedingung von Demokratie, die er als Lebensform ihrer Bürger:innen versteht. Demokratie lebt insofern von der Mitgestaltung durch die Bürger:innen. Bildung hat demnach die Aufgabe, zu Mündigkeit und Mitgestaltung zu verhelfen, wozu ganz wesentlich auch der kritisch-konstruktive Umgang mit Information und deren Quellen gehört [7, p. 7 f.].

Wenn im Zuge der fortschreitenden Digitalisierung künstliche Intelligenz so weiter entwickelt wird, dass sie künftig die Steuerung der Informationsbereitstellung für uns Menschen ohne unser Zutun übernimmt, stellt uns das vor die Herausforderung zu erkennen, ob und wie wir als Menschen Subjekt sein und bleiben können. Die Voraussetzungen für eine Kultivierung von Mündigkeit gewinnen dadurch an Komplexität und die Wahrscheinlichkeit ihrer Realisierbarkeit wird in Frage gestellt.

Umso mehr sehen wir die Notwendigkeit, die Bedingungen von Mündigkeit und verantwortlicher Mitgestaltung der zunehmend digitalisierten Welt, die Voraussetzungen verlässlicher und belastbarer Information und die Möglichkeit von Verständigung im Sinne von intersubjektivem Verstehen zu erforschen.

C. Kooperationspartner

Kontextualisierte Forschung erfordert eine Einbettung in vielfältige Wirklichkeitsfelder. Deshalb sind in das Projekt KoDiA Kooperationspartner aus ganz unterschiedlichen Bereichen eingebunden:

ABBILDUNG 2: KOOPERATIONSPARTNER IM KODIA-PROJEKT.

Innerhalb der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg ermöglichen das Medienzentrum und das Rechenzentrum, über Bildung für eine digitale Arbeits- und Lebenswelt nicht nur zu philosophieren und zu diskutieren, sondern Digitalität in Bildung und Beruf praktisch zu erproben. Im Vordergrund der Zusammenarbeit mit dem Medienzentrum stehen dabei hybride Raumkonzepte, die Lehr-, Lern- und Veranstaltungsräume mit virtuellen Räumen verbinden. Die Kooperation mit dem Rechenzentrum fokussiert unter anderem die Einbettung von innovativen IT-Services wie zum Beispiel Rechenleistung und Speicherkonzepte für Forschungsdaten.

Im wissenschaftlichen Umfeld bringt sich das Institut für technische Informatik, Mathematik und Operations Research unserer Schwesteruniversität in München (UniBw M) unter Leitung von Professor Dr. Stefan Pickl in technologische Entwicklungen virtueller Bildungs-, Forschungs- und Konferenzumgebungen ein. Das Bundesinstitut für Berufsbildung (BIBB) ist mit der Abteilung 4 „Initiativen für die Berufsbildung“ unter Leitung von Professor Dr. Michael Heister in die Entwicklung und Erprobung von Bildungsprodukten für eine digitale Arbeitswelt in der dualen Berufsausbildung eingebunden. Schwerpunkt ist dabei die Sicherung der Anschlussfähigkeit an Vorgaben und Entwicklungsperspektiven der geregelten beruflichen Bildung bundesweit. Die Professur für Berufs- und Wirtschaftspädagogik der Pädagogischen Hochschule Freiburg (PH Freiburg) unter Leitung von Professorin Dr. Juliana Schlicht realisiert einen wesentlichen Anteil des Arbeitspakets 3 zum Aufbau eines interdisziplinären Forschungsnetzwerks in Form eines „Innovationslabors „Berufliche Bildung für eine innovative Energiewende unter Nutzung digitaler Technologien für den virtuellen Austausch“ [8] (vgl. Schlicht 2022).

Die Erforschung von Bildung für die digitale Arbeitswelt erfordert vor allem berufliche Bildungskontexte. Diese werden im Projekt in Zusammenarbeit mit dem Hamburger Institut für Berufliche Bildung (HIBB) in acht Bildungsgängen an insgesamt sieben Hamburger Berufsschulen erschlossen. Darüber hinaus werden außerhalb der dualen Berufsausbildung auch Kooperationsbeziehungen mit Ausbildungseinrichtungen der Bundeswehr aufgebaut: Die Logistikschule der Bundeswehr (LogSBw) entwickelt mit dem Projekt „Modernes Lernen“ bereits seit einigen Jahren neue Formen einer handlungs- und kompetenzorientierten Logistikausbildung, die auch unter Nutzung der Möglichkeiten technologiegestützter Ausbildung besonders innovative Wege beschreitet. Die Abteilung Ausbildung Streitkräfte im Streitkräfteamt der Bundeswehr (SKA Abt AusbSK) entwickelt zentral für alle Teilstreitkräfte und Organisationsbereiche der Bundeswehr seit den frühen 2000er Jahren die dafür erforderlichen technischen Ressourcen, Plattformumgebungen und Anwendungen, koordiniert als fachlich zuständige Stelle die Ausbildung von Teletutoren der Bundeswehr und hat die Leitung des alle Aktivitäten der Bundeswehr rund um technologiegestützte Ausbildung vertretenden Gremiums „Arbeitsgruppe technologiegestützte Ausbildung (AG TA)“. Die Abteilung Ausbildung Streitkräfte verfügt somit über rund 20 Jahre Erfahrung in der Realisierung technologiegestützter und kompetenzorientierter Ausbildung in der Bundeswehr unter den besonderen Rahmenbedingungen einer komplexen Großorganisation für Aufgabenstellungen im Einsatz sowie im Grundbetrieb. Aktuell entwickelt die AG TA neue Regelungsgrundlagen für die technologiegestützte Ausbildung unter den Rahmenbedingungen einer auch in der Bundeswehr fortschreitenden Digitalisierung, unter anderem ein neues „Ausbildungskonzept technologiegestützte Ausbildung“. Mit der initialen Entwicklung der über das Internet verfügbaren Plattform „Link and Learn“, die eine Vielzahl bekannter OpenSource-Anwendungen in einer einheitlichen Benutzeroberfläche integriert, hat die Abteilung Ausbildung Streitkräfte darüber hinaus Maßstäbe für eine Nutzergerechte virtuelle Lernumgebung in die Praxis gebracht. Das Hosting dieser zukunftsweisenden Plattform hat inzwischen die IT-Schule der Bundeswehr (ITSBw) übernommen, die auch deren technische Weiterentwicklung gemäß Anforderungen der verschiedenen Nutzergruppen vorantreibt. Auch mit der ITSBw streben wir eine Kooperation im Projekt KoDiA an, um Entwicklungsbedarfe an die virtuelle Plattformumgebung, die eine Bildung für die digitale Arbeitswelt (nicht nur) in der Bundeswehr im Rahmen des Forschungsprozesses erkannt werden, praktisch umzusetzen und wiederum in verschiedenen Praxisfeldern zu erproben. Daraus entsteht eine iterative, dialogische und gleichberechtigte Weiterentwicklung von Konzepten, Lösungen und Anwendungserfahrungen, die unmittelbar in der Bildungs-, Berufs- und Lebenspraxis nutzbar wird.

III. Bildung für die digitale Arbeitswelt im Kontext dualer Ausbildung

Wenn Bildung einen Beitrag dazu leisten kann, dass Menschen als mündige Bürgerinnen und Bürger an der fortschreitenden Digitalisierung in ihrer Arbeits- und Lebenswelt teilhaben und wir damit auch den Anspruch an einen gerechten Zugang für den dazu erforderlichen Kompetenzerwerb verbinden, kommt der beruflichen Bildung besonderer Stellenwert zu. Einen Bildungsauftrag, der über die rein funktionalen Fähigkeiten zur Erfüllung einer beruflichen Aufgabe in betrieblichen Kontexten hinausreicht, übernehmen dabei für die dualen Ausbildungsgänge die Berufsschulen [9, p. §2].

Deshalb bieten die Berufsschule den Kontext, in dem das Forschungsprojekt KoDiA ansetzt, um zu erproben, wie konkret schulische Berufsbildung zur Mitgestaltung von Digitalisierung in der Arbeitswelt beitragen kann. Im Vordergrund steht dabei die Ertüchtigung des Subjekts, wobei wir mit unserem Verständnis vom Subjekt an die Arbeiten von Klaus Holzkamp [10] anknüpfen.

Handlungs- und forschungsleitend ist das Neun-Dimensionen-Modell, das wir in zahlreichen Forschungs- und Implementierungsprojekten entwickelt und eingesetzt haben [11, pp. 51 - 57], [12]. Es bietet einen Rahmen, um systematisch und transparent Bildungskonzepte von einer theoretischen Meta-Ebene in die konkrete Bildungspraxis zu bringen und dabei gewonnene Erkenntnisse in den theoretischen Bezugsrahmen zurück zu übersetzen. Theorie und Praxis werden auf diese Weise iterativ miteinander verbunden. Diese Vorgehensweise ist eine auf Forschungsprozesse adaptierte und weiterentwickelte Form der „vollständigen Handlung“ [5, p. 4 ff.] (vgl. Schulz und Neusius 2020, S. 4 ff.).

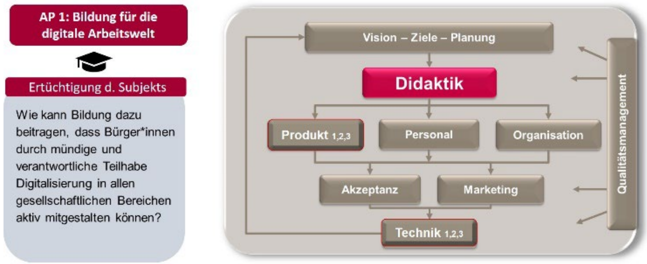


ABBILDUNG 3: NEUN-DIMENSIONEN-MODELL IM ARBEITSPAKET 1.

Der Forschungs- und Entwicklungsprozess erfolgt im Rahmen von Workshops, die gemäß dem 9-Dimensionen-Modell gegliedert sind und in denen die beteiligten Berufsschulen ihre Bildungsprodukte zur Förderung der mündigen Teilhabe an der Digitalisierung der Arbeitswelten in den jeweiligen Berufen erarbeiten. Die folgenden Dimensionen sind im Modell enthalten [12, pp. 51 - 57], [5, p. 5 f.]:

Vision – Ziele – Planung: Auf Ebene der Projektverantwortlichen aller beteiligten Stakeholder gilt es, zu Beginn der Zusammenarbeit gemeinsame Zielvorstellungen, strategische Perspektiven und Rahmenbedingungen der Projektplanung abzustimmen.

Didaktik: In Bildungsprojekten ist die Entscheidung für eine pädagogisch-didaktische Grundorientierung für alle weiteren Konzeptions- und Realisierungsschritte essenziell, da die Vorgehensweise für die Konzeptentwicklung und deren Umsetzung in der Bildungspraxis nur aus den zuvor definierten pädagogisch-didaktischen Grundannahmen abgeleitet werden kann.

Produktentwicklung: Es geht um die Konzeption und Umsetzung neuer Bildungskonzepte im Rahmen konkreter Bildungsgänge und / oder Bildungsmaßnahmen. Diese sind als Produkt zu verstehen und der Prozess der Produktentwicklung ist gemeinsam mit allen beteiligten Stakeholdern zu gestalten.

Personalentwicklung: Wenn in Bildungseinrichtungen neue didaktisch-methodische Modelle umgesetzt werden sollen und z.B. unter einem kompetenzorientierten didaktischen Paradigma digitale Lern-, Lehr-, Arbeits- und Übungsumgebungen eingesetzt werden sollen, benötigen die mit deren praktischen Umsetzung betrauten Lehrpersonen (Lehrer*innen, Ausbilder*innen, Dozent*innen, Trainer*innen) Handlungssicherheit nicht nur in der funktionalen Handhabung sondern auch in deren didaktisch sinnvoller Nutzung.

Organisationsentwicklung: Die Umstellung auf ein neues pädagogisch-didaktisches Paradigma, auf neue didaktisch-methodische Gestaltungsformen von Lehr-Lern-Settings und auf die Nutzung neuer Verfahren und Technologien in der didaktischen Gestaltung des Lernens, Lehrens, Arbeitens und Übens erfordert in der Regel andere Prozesse und andere Formen der Zusammenarbeit als bisherige Routinen. Dies wird zumeist bereits im Kontext der Projektierung spürbar. Eine nachhaltige Entwicklung erfordert auch Weiterentwicklungen und neue Wege in der organisationalen und prozessualen Struktur der beteiligten Institutionen.

Akzeptanzsicherung: Die Einführung neuer Verfahren, damit einhergehende strukturelle und organisationale Veränderungen und die Notwendigkeit, Neues zu lernen erfordern von den beteiligten Akteur*innen erheblichen Mehraufwand. Dabei entstehen mitunter Vorbehalte, Ängste und Lernbedarfe, die im Rahmen des Projekts beachtet und thematisiert werden sollten.

Marketing: Besonders dann, wenn die Teilnahme freiwillig ist, aber auch wenn sie obligatorisch ist, ist es wichtig, die Adressaten eines neuen Bildungsangebots über die Neuerungen und damit verbundenen Potenziale zu informieren.

Technik: Die Umsetzung von Maßnahmen zur Förderung des Kompetenzerwerbs für die digitale Arbeitswelt erfordert die Bereitstellung und Nutzung digitaler Technologien. Die Funktionsanforderungen ergeben sich aus den pädagogisch-didaktischen Grundannahmen und daraus abgeleiteten methodischen Ansätzen. Wichtig ist dabei, auch konzeptionelle Weiterentwicklungspotenziale bei der technischen Umsetzung im Blick zu haben, da nur so eine nachhaltige Implementierung und Entwicklung gewährleistet werden kann.

Qualitätsmanagement: Im Verständnis eines iterativen und agilen Stakeholder-, Prozess- und Projektmanagements bedürfen die Realisierungsschritte in allen o.g. Dimensionen einer kontinuierlichen, prozessbegleitend querschnittlichen Reflexion hinsichtlich des Beitrags zur Erreichung der vorgegebenen und / oder selbstgesetzten Ziele.

Das Modell strukturiert die methodische Vorgehensweise der Erprobung und damit Erforschung von Bildungsprodukten, die an den beteiligten Berufsschulen entstehen. Zu allen Dimensionen werden in der oben skizzierten Reihenfolge Workshops an allen Schulen und in allen Bildungsgängen, die in das Projekt eingebunden sind, durchgeführt. Die Schulen haben auf diese Weise aus den Lernfeldern der jeweiligen Ausbildungsberufe konkrete Handlungs- und Lernsituationen erarbeitet, für die ihr Bildungsprodukt entwickelt werden soll.

Der didaktische Ausgangspunkt sind Forschungen des Zentrums für technologiegestützte Bildung zu handlungs- und kompetenzorientierter Aus-, Fort- und Weiterbildung mit Erwachsenen unter den Bedingungen der Digitalisierung, zu denen wir im Rahmen des pädagogisch-didaktischen Konzepts der Fernausbildung in den vergangenen Jahren umfangreich publiziert haben [13], [14], [12]. Die Erkenntnisse, die der Entwicklung des pädagogisch-didaktischen Konzepts der Fernausbildung zugrunde liegen, sind jedoch außerhalb der dualen Berufsausbildung entstanden. Die Kontexte, die diesen Forschungen zugrunde lagen, sind vielfältig: Sie umfassen verschiedene Handlungsfelder militärischer Ausbildung, der Fort- und Weiterbildung von Führungskräften sowohl im militärischen als auch im zivilen Bereich, der beruflichen Rehabilitation sowie der Weiterbildung im privatwirtschaftlichen Kontext. Eine zentrale Erkenntnis dieser Forschungen ist, dass die Möglichkeiten der Umsetzung auf Handlungskompetenz und damit aktive Mitgestaltung zielender technologiegestützter Bildung entscheidend gerahmt sind von den institutionellen, organisationalen und vor allem auch rechtlichen Bedingungen des jeweiligen Umfeldes.

Die Einbettung in den Kontext der Bildungswirklichkeit an den beteiligten Berufsschulen ermöglicht deshalb, die bisherigen Entwicklungen und Erkenntnisse und die daraus entstandenen konzeptionellen – theoretischen – Ideen unter den Bedingungen der Lernortkooperation zwischen Berufsschulen, Betrieben und überbetrieblichen Bildungsstätten zu erproben. Es geht dabei um die Förderung von Kompetenzen der Mitgestaltung der Digitalisierung in der Lebens- und Arbeitswelt, deshalb steht die Einbindung digitaler Verbreitungsmedien in die entstehenden Bildungsprodukte im Fokus einer didaktischen Betrachtung. Die Erschließung des virtuellen Raums als einem neuen Lernort, der im Rahmen der Lernortkooperation womöglich zukünftig eine Brücke zwischen den physikalischen Lernorten sein kann, ist ebenfalls Gegenstand der Forschung.

Einen wichtigen Anknüpfungspunkt für die Frage, welche allgemeinen Handlungsfelder didaktisch zu berücksichtigen sind, um die Kompetenzentwicklung für einen kritisch-konstruktiven Umgang mit digitalen Technologien in privatem und beruflichem Alltag zu fördern, bilden die Kompetenzbereiche, die die Kultusministerkonferenz in ihrer 2017 veröffentlichten Strategie „Bildung in der digitalen Welt“ für Schule und berufliche Bildung identifiziert hat [15, p. 16 ff.]:

- Suchen, Verarbeiten und Aufbewahren

  Suchen und filtern, auswerten und bewerten, speichern und abrufen

- Kommunizieren und Kooperieren

  Interagieren, teilen, zusammenarbeiten, Umgangsregeln kennen und einhalten, an der Gesellschaft aktiv teilhaben

- Produzieren und Präsentieren

  Entwickeln und produzieren, weiterverarbeiten und integrieren, rechtliche Vorgaben beachten

- Schützen und sicher agieren

  Sicher in digitalen Umgebungen agieren, persönliche Daten und Privatsphäre schützen, Gesundheit schützen, Natur und Umwelt schützen

- Problemlösen und Handeln

  Technische Probleme lösen, technische Werkzeuge bedarfsgerecht einsetzen, eigene Defizite ermitteln und nach Lösungen suchen, digitale Werkzeuge zum Lernen, Arbeiten und Problemlösen nutzen, Algorithmen erkennen und formulieren

- Analysieren und Reflektieren

  Medien analysieren und bewerten, Medien in der digitalen Welt verstehen und reflektieren

Für die Berufsschulen als Lernort der beruflichen Bildung ergeben sich daraus gemäß der Digitalstrategie der KMK [15, p. 21 ff.] folgende abstrakte Anforderungen, die im Rahmen der Unterrichtsgestaltung in den Lernfeldern zu konkretisieren und so auch im Rahmen der Produktentwicklung in unserer Forschung zu berücksichtigen sind:

- Anwendung und Einsatz von digitalen Geräten und Arbeitstechniken
- Personale und berufliche Handlungsfähigkeit
- Selbstmanagement und Selbstorganisationsfähigkeit
- Internationales Denken und Handeln
- Projektorientierte Kooperationsformen
- Datenschutz und Datensicherheit
- Kritischer Umgang mit digital vernetzten Medien und den Folgen der Digitalisierung für die Lebens- und Arbeitswelt

Einen weiteren konzeptionellen Ankerpunkt bildet das „Frankfurt-Dreieck“, das in Weiterentwicklung der von der Gesellschaft für Informatik herausgegebenen Dagstuhl-Erklärung „Bildung in der digital vernetzten Welt“ [16] als interdisziplinäres Modell [17] für die schulische und außerschulische Bildung vorgeschlagen wurde.

Die Dagstuhl-Erklärung [16, p. 3] fordert eine Auseinandersetzung mit der digital vernetzten Welt im Rahmen schulischer Bildung in drei Dimensionen:

- Technologische Perspektive: „Wie funktioniert das?“
- Gesellschaftlich-kulturelle Perspektive: „Wie wirkt das?“
- Anwendungsbezogene Perspektive: „Wie nutze ich das?“

Im „Frankfurt-Dreieck“ erweitert die Gesellschaft für Informatik diesen Ansatz über die schulische Bildung hinaus um die Prozessebene der Analyse, Reflexion und Gestaltung, die in allen drei Perspektiven beachtet werden sollen [17]. Daraus ergibt ich folgendes Modell:

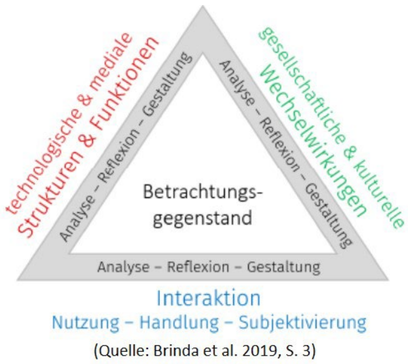


ABBILDUNG 4: FRANKFURT-DREIECK FÜR BILDUNG IN DER DIGITAL VERNETZTEN WELT.

IV. ÖFFENTLICHE WISSENSCHAFT ALS BASIS INNOVATIVER KOOPERATIONEN

Die Erschließung des virtuellen Raums nimmt auch für den Transfer des theoretischen Ansatzes einer Öffentlichen Wissenschaft in den konkreten Kontext gesellschaftlicher Öffentlichkeiten einen zentralen Stellenwert ein.

Wenn im Rahmen des Forschungsprojekts Bildung für die digitale Arbeitswelt kontextualisiert, konkretisiert und erprobt werden soll mit dem Ziel, die aktive und mündige Mitgestaltung der fortschreitenden Digitalisierung zu fördern, benötigen die Subjekte, um deren Teilhabe an Digitalisierung es geht, einen Referenzrahmen, der ihnen hilft, sich in der Auseinandersetzung mit der Digitalität als neuem Verbreitungsmedium (Schrift, Buchdruck, Massenmedien und elektronische Medien) und auch neuem Erfolgsmedium (Geld, Macht, Wahrheit, Recht, Kunst, Liebe) der Gesellschaft [2, p. 10] zu positionieren zwischen Anpassung und Widerstand, Affirmation und Eigensinn.

Baecker [2, p. 11] beschreibt Komplexität als Möglichkeit, mit dem Überschusssinn, den digitale Medien erzeugen, als Gesellschaft umzugehen:

„Digitalisierung als sozialer und kultureller Prozess […] ist ein Prozess der rasant zunehmenden Beteiligung ‚intelligenter’ Maschinen an Kommunikation, die […] als selektive Vernetzung subjektiv eigensinniger Akteure […] zu verstehen ist“ [2, p. 17]. Baecker skizziert, dass in dem Erleben der

Nicht-Berechenbarkeit der durch komplexe Algorithmen gesteuerten – und so eben nicht mehr analogen steuerbaren – Aktionen von Maschinen, bzw. Interaktionen zwischen Mensch und Maschine zugleich ein Unwohlsein des nicht mehr Überblickens aber auch eine Entlastungserfahrung des sich Anpassens an das, was die Maschine zulässt. „Es ist kein Zufall, dass Gamification zum Paradigma einer Einübung in die sozialen, nicht technischen Prozesse der Digitalisierung geworden ist" [2, p. 18].

Ein Dilemma, das Baecker hier anspricht, ist das zwischen Impulsivität und Reflexivität, zwischen sich treiben lassen und bewusst agieren. Eine Mitgestaltung der Digitalisierung erfordert bewusstes Agieren, also Reflexivität und diese wiederum erfordert ein Koordinatensystem aus Entscheidungskriterien.

Bewusste Entscheidungen sind informierte Entscheidungen und Informationen können wir aus unterschiedlichen Quellen gewinnen: Eigene Erfahrung, Überlieferung und alle Arten externer Informationsquellen.

2021 haben eine Untersuchung der Stiftung Neue Verantwortung [18] (vgl. Meßmer, Sängerlaub und Schulz) für die Gesamtbevölkerung und eine PISA-Sonderauswertung für Jugendliche im Alter von 15 Jahren [19] aufgezeigt, dass die Kompetenz zur Einordnung im Internet verfügbarer Informationen hinsichtlich ihrer Seriosität, also die Fähigkeit zur Unterscheidung zwischen Fakten, Meinung und Fake News, im Durchschnitt relativ gering ausgeprägt ist. Woher also kann ein Referenzrahmen kommen, der hilft, Informationen für unsere Positionierung zwischen Anpassung und Widerstand unter Bedingungen der Digitalisierung zu gewinnen, die verlässlich und belastbar sind?

Solche Informationen bereit zu stellen, ist das ureigenste Geschäft von Wissenschaft, die sich allgemeinen Standards und Qualitätskriterien von Wissenschaft, wie sie z.B. Jürgen Bortz und Nicola Döring in ihrem Lehrbuch „Forschungsmethoden und Evaluation" in einem Modell systematisieren, verpflichten [20, p. 90 ff.]. Ein Problem ist aber die Kommunikation im Sinne von Information (Sachbezug), Mitteilung (Sozialbezug) und Verstehen (Reproduktion), die sich „auf verschiedene Adressen (Ego und Alter Ego), verschiedene zeitliche Momente und verschiedene Wahrscheinlichkeiten (Kontextbedingungen)" beziehen [2, p. 17]: Wie können Wissenschaft und Öffentlichkeit miteinander kommunizieren, so dass Wissenschaft der Öffentlichkeit relevante Informationen verständlich und damit nutzbar anbietet und reicht das?

„Nicht nur die Wissenschaft muss sich auf die Problemlagen und Anforderungen einer modernen Gesellschaft besser einstellen, auch Erkenntnis- und Wissenschaftstheorie muss dem damit verbundenen Reflexions- und Vermittlungsbedarf gerecht werden. Wie bei jedem entwickelten Diskurs besteht auch hier die Gefahr, dass sich die Experten nur noch mit ihren eigenen Fragestellungen und Problemen beschäftigen. Daher ist auch hier ein Nachfragen und eine Einmischung des (Laien-)Publikums wichtig und hilfreich, weil es die Experten dazu bringt, ihr Können auf externe, allgemein wichtige Probleme einzustellen" [21, p. 258 f.].

Hier setzt die Idee der Öffentlichen Wissenschaft an. Wir erweitern damit das Konzept einer Öffentlichen Soziologie, wie es von Michael Burawoy (2015) vorgeschlagen [22] und im deutschsprachigen Raum vor allem von Brigitte Aulenbacher, Klaus Dörre und Johanna Sittel aufgegriffen wurde [1], [23, p. 5]. In der deutschsprachigen Adaption wird der Diskurs einer Öffentlichen Soziologie begründet als Beitrag der Soziologie für eine gesellschaftliche Transformation im Modus der Krise. Die Protagonisten des Ansatzes, die der Jenaer Arbeitsgruppe „Postwachstumsgesellschaft" angehören, sehen darin ein Programm zur Stärkung der Resilienz der demokratischen Zivilgesellschaft gegenüber extremistischen, totalitären und antidemokratischen Tendenzen: Wenn sich die Soziologie als Wissenschaft der Gesellschaft und ihrer Entwicklungsdynamiken einem öffentlichen Diskurs im Sinne eines Dialogs mit Öffentlichkeiten außerhalb der Wissenschaft in der Weise öffnet, dass eine Interaktion auf Augenhöhe möglich ist, kann Sie dazu beitragen, Bedingungen, Voraussetzungen und Wirkungszusammenhänge z.B. technologischer und gesellschaftlicher Entwicklung zu erklären und Ansätze zu finden, wie Entwicklungen gemeinsam gestaltbar sind [1, p. 4 ff.], [24, p. 144]. Die Einbettung in die Auseinandersetzung mit Gesellschaften in Krisen ist insofern interessant, als die wesentlichen Veröffentlichungen zum Ansatz einer Öffentlichen Soziologie vor der Covid-19-Krise, vor dem Beginn des Angriffskrieges Russlands gegen die Ukraine und vor der damit verschärften Energiekrise entstanden sind.

Dabei geht es eben nicht im Schwerpunkt um Wissenschaftskommunikation, in deren Rahmen DIE Wissenschaft DER Öffentlichkeit DIE Welt erklärt (die Konstrukte „Wissenschaft", „Öffentlichkeit" und „Welt" bedürften einer eigenen philosophischen Einordnung, auf die wir hier aber gerne verzichten möchten). Vielmehr geht es darum, dass Wissenschaftler:innen ihre Forschungen, ihre Erkenntnisse und ihre Theorien für verschiedene Öffentlichkeiten nutzbar machen, indem sie sie adressatengerecht und auf konkrete Herausforderungen der Gesellschaft bezogen erläutern. Zugleich fordert der Ansatz einer Öffentlichen Wissenschaft, dass Wissenschaftler:innen sich den Fragen und Erfordernissen der Gesellschaft öffnen und von außerwissenschaftlichen Öffentlichkeiten erfahren, zu welchen Fragestellungen Forschung erforderlich und relevant ist [1, p. 5; 10 ff.], [23, p. 8].

Bezogen auf unseren Forschungsgegenstand einer fortschreitenden Digitalisierung in allen Sphären der Gesellschaft könnte Öffentliche Wissenschaft als Bezugsrahmen in einem Dialog zwischen Wissenschaft und gesellschaftlicher Öffentlichkeit zum Beispiel zu den in der ABBILDUNG 5 benannten Aspekten einsetzen:

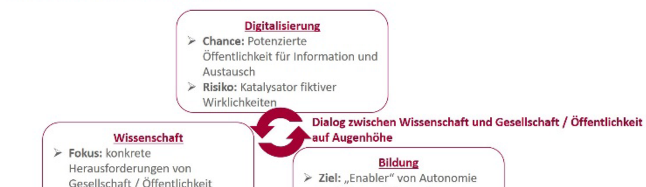


ABBILDUNG 5: ASPEKTE ÖFFENTLICHER WISSENSCHAFT IM KODIA-PROJEKT.

Dabei stellt sich die Frage, wie genau Öffentliche Wissenschaft ihre Öffentlichkeiten (wir verwenden den Begriff der Öffentlichkeiten hier im Plural, weil gesellschaftliche Öffentlichkeit in unserem Verständnis keine homogene, singuläre Einheit darstellen kann, sondern gesellschaftliche Öffentlichkeit in verschiedensten Sphären anzutreffen ist: Öffentlichkeiten konkretisieren und kontextualisieren sich z.B. in der Bildungspraxis, im Sport, in der Politik, in verschiedenen Bereichen des kulturellen Lebens oder samstagsnachmittags in der

Fußgängerzone [22, p. 56]) erreichen und mit ihren Akteur:innen in Dialog treten können:

Eine erste Assoziation mag ein hierarchisches Modell sein, in dem Wissenschaftler:innen ihre Erkenntnisse und Theorien einer außerwissenschaftlichen Öffentlichkeit erklären. In diesem Modell sind die Wissenschaftler:innen die Wissenden und die Akteur:innen der Öffentlichkeit diejenigen, die belehrt werden. Im akademischen Alltag ist dieses Modell heute noch weit verbreitet.

Eine zweite Möglichkeit wäre das Ideal einer gleichrangigen Interaktion auf Augenhöhe, in dem Wissenschaftler:innen und Öffentlichkeiten einander direkt begegnen und miteinander in Austausch treten. Das kann erfolgreich sein in dem Sinne, dass Repräsentant:innen beider „Welten" einander ohne weiteres verstehen. Allerdings birgt eine solche Konstellation das Risiko, dass beide aneinander vorbei kommunizieren, denn nicht immer gelingt eine adressatengerechte Kommunikation auf Anhieb. Es bedarf einiger Kenntnis der Lebenswirklichkeiten und -interpretationen des jeweiligen Gegenübers, damit unmittelbare Kommunikation gelingen kann.

In unserem Forschungsprojekt erproben wir die Idee eines „Agenturmodells". Das Besondere an dieser Herangehensweise ist, dass wir zwischen Akteur:innen der Wissenschaft und Akteur:innen der Öffentlichkeit, die wir hier definieren als lebensweltliche Praxisfelder, eine Mittlerfunktion sehen. Um diese Mittlerfunktion auszufüllen, ist es erforderlich, sich im Vorfeld einer Begegnung mit den Akteur:innen aus Wissenschaft und Praxis (Öffentlichkeit) gezielt über deren wahrscheinliche Interessen- und Bedürfnislagen zu informieren. Gezielt kann dies nur dann erfolgen, wenn ein Themenfeld, das im Fokus der Begegnung stehen soll, benannt und definiert ist.

Die Umsetzung eines Agenturmodells für Öffentliche Wissenschaft erfordert neben der Vergewisserung über mögliche Interessen der Beteiligten aber auch, dass die Agentur sowohl durch die Öffentlichkeit als auch durch die Wissenschaft wahrgenommen und in ihrer Funktion als Mittler zwischen beiden Welten akzeptiert wird. Zudem ist zu überlegen, welche Kommunikationsformate und -dimensionen für einen durch die Agentur moderierten Austausch in Frage kommen.

Eine zentrale Fragestellung für die Erforschung des Agenturmodells Öffentlicher Wissenschaft ist demnach, wie im virtuellen Raum ein Dialog zwischen Wissenschaft und gesellschaftlicher Öffentlichkeit erfolgen kann, um relevante Forschungsbedarfe zu identifizieren und Forschung für die Gesellschaft nutzbar zu machen [5, p. 6].

Das Agenturmodell Öffentlicher Wissenschaft kann folglich nur kontextualisiert erprobt und erforscht werden. Im Rahmen unseres Forschungsprojektes realisieren wir diese Kontextualisierung in Form so genannter Use Cases, also konkreter Anwendungsfälle. Vor dem Hintergrund der Digitalisierung sowohl der wissenschaftlichen als auch der öffentlichen gesellschaftlichen Praxis erachten wir es als wichtigen Aspekt unserer Forschung, den virtuellen Raum als Ort der moderierten Begegnung in unsere Betrachtung mit einzubeziehen. Für eine Kontextualisierung stellen wir deshalb hybride Anwendungsszenarien in den Vordergrund. Hybrid verstehen wir dabei als eine Form der Interaktion und Kommunikation, die sowohl in einem Präsenzformat als auch gleichzeitig mit Einbindung von Akteur:innen, die nicht am selben Ort zugegen sind, online erfolgt.

In einem ersten Experiment konnten wir ein solches hybrides Format im Mai dieses Jahres in einer Fachtagung zum Thema „Perspektiven der Subjektbildung" testen. Die Umsetzung Öffentlicher Wissenschaft stand dabei noch nicht im Fokus, vielmehr ging es darum, Erfahrungen mit themenbezogen moderierten hybriden Interaktionsformen zu gewinnen. Interessanterweise haben sich als Teilnehmende sowohl in Präsenz als auch online dabei nicht nur Vertreter:innen der Wissenschaft sondern auch Akteur:innen der Bildungspraxis beteiligt und sich auch aktiv in die Diskussionen zum Thema eingebracht.

Als zentralen Use Case für das Agenturmodell Öffentlicher Wissenschaft integrieren wir den (Aus)Bildungskongress der Bundeswehr, den wir als teilvirtuelle Veranstaltung mit skalierbaren Präsenzanteilen weiterentwickeln. Ein Anliegen des (Aus)Bildungskongresses der Bundeswehr bestand schon immer darin, Wissenschaft und Bildungspraxis einander näher zu bringen und ein Ort der Begegnung und des Austauschs zu sein. Die adressatengerechte Gestaltung eines Tagungsprogramms und einer Fachausstellung, die diesem Gedanken Rechnung tragen, stellt dabei seit jeher eine große Herausforderung dar. Dass es einer Mittlerfunktion bedarf, um die Möglichkeiten gelingender, also für beide Seiten erkenntnis- und gewinnbringender Interaktion zu schaffen, ist eine Erfahrung, die wir aus fast 20 Jahren als Kongressveranstalter mit diesem Anspruch gewinnen konnten.

Die Integration des virtuellen Raums als zusätzlicher Dimension, die nicht nur eine räumliche Erweiterung sondern auch eine Chance auf Teilhabe von Akteur:innen bietet, die aus verschiedensten Gründen nicht vor Ort sein können, bietet uns einen neuen Anknüpfungspunkt. Sie ist sowohl Forschungsgegenstand als auch Möglichkeitsraum praktischer Erfahrung.

V. Aufbau eines querschnittlichen Forschungsnetzwerks als mögliche Antwort auf die „False-Balance-Problematik"

Niklas Luhmann hat bereits 1990 (S. 341) festgestellt: „Das Risiko der Ausdifferenzierung eines besonderen Funktionssystems Wissenschaft liegt aber nicht im Abwerfen der Zügelung durch soziale Kontrolle, und es liegt auch nicht in der Gefahr von Verstößen gegen die Moral. Es liegt in der funktionalen Spezifikation selber. Im Kontext einer funktional differenzierten Gesellschaft bedeutet funktionale Spezifikation Redundanzverzicht" [25].

Ein solcher Redundanzverzicht zeitigt wiederum unterschiedliche Risiken, die das Verhältnis der Funktionssysteme „Wissenschaft" und „Öffentlichkeit" kennzeichnen und markiert im Grunde das Ende des Diskurses im Ringen um Erkenntnis.

Während wir im vorangegangenen Abschnitt den Fokus auf das Wechselverhältnis zwischen Wissenschaft und Öffentlichkeit gerichtet haben, sehen wir im Weiteren auch die Frage, wie die zunehmende Binnendifferenzierung des Funktionssystems Wissenschaft sich auf Interaktionsbeziehungen nach innen und außen auswirkt als bedeutsam an.

Zum einen kann das oben beschriebene Agenturmodell Öffentlicher Wissenschaft nur dann in konkrete Kontexte gestellt werden, wenn aus Öffentlichkeit und Wissenschaft relevante Forschungs- und Handlungsfelder in Zusammenhang gebracht werden können. Das erfordert für die Agentur zunächst einmal die Kenntnis darüber, welche Handlungsfelder gesellschaftlichen, öffentlichen Lebens- und Arbeitswirklichkeiten Fragestellungen an Wissenschaft und Forschung erzeugen und die Kenntnis darüber, wo in Wissenschaft und Forschung dazu bereits Anknüpfungspunkte bestehen oder vermutet werden können.

Darüber hinaus konnten wir während der Covid-19-Krise erleben, welches Irritationspotenzial darin liegt, wenn wissenschaftliche Diskurse, die in normalen Zeiten disziplinintern erfolgen, plötzlich im Angesicht einer die gesamte Gesellschaft betreffenden Krise ungefiltert in die breite Öffentlichkeit getragen und medial in einer Weise transportiert werden, dass eine Einordnung der oft nur vermeintlich konträren Positionen für das Publikum nicht möglich ist. Das Phänomen der „false balance“ wurde seither auch in den Feuilletons der überregionalen Medien [26] vielfach kritisch beschrieben.

Eine weitere Herausforderung, die nicht nur den Zugang zu einer Öffentlichen Wissenschaft erschwert, sondern auch den intra- und interdisziplinären Diskurs im Sinne des im eingangs angeführten Zitat von Niklas Luhmann als „Redundanzverzicht bezeichneten Phänomens beschreibt, ist die zunehmende intradisziplinäre Fragmentierung, die wir zumindest in den Geistes- und Sozialwissenschaften in den letzten Jahrzehnten beobachten [27].

Vor dem Hintergrund der oben skizzierten Problemlage, entwickeln wir in unserem Forschungsprojekt Wege für den intra- und interdisziplinären Diskurs, der ähnlich wie für die Erforschung Öffentlicher Wissenschaft konkrete Kontexte benötigt, die Anlass und Raum für den Austausch zwischen Wissenschaftler:innen bietet. Dazu entwickeln wir ein querschnittliches interdisziplinäres Forshcungsnetzwerk mit perspektivisch allen Projekten und Akteur:innen des dtec.bw, um gemeinsame Forschungsinteressen und -zugänge zu identifizieren und damit Chancen für eine synergetische Nutzung der über dtec.bw bereitgestellten Ressourcen zu eröffnen. Der in dtec.bw zumindest virtuell entstehende gemeinsame Forschungszusammenhang von Wisseschaftler:innen nahezu aller denkbaren Fachdisziplinen und -kulturen bietet hier ein weites Feld der Exploration. Dieses bedarf einer weiteren Konkretisierung und Kontextualisierung, um über konkrete Forschungsfragen, methodische Zugänge und Definitionen auch über den „Tellerrand“ des je eigenen Projektes hinaus zu diskutieren und womöglich Korridore für Konsens zu entdecken.

Mit einem ersten Teilprojekt erproben wir diesen Zugang zum intra- und interdisziplinären Austausch gemeinsam mit Juliana Schlicht mit dem Aufbau eines Innovationslabors Berufliche Bildung für eine innovative Energiewende, kurz: InnoLab BBEW [8].

VI. Fazit und Auslick

Im Rahmen unseres dtec.bw-Forschungsprojektes KoDiA erforschen und erproben wir, wie Bildung Kompetenzen für eine fortschreitend digitalisierte Lebens- und Arbeitswelt einen Beitrag zu Bildungsgerechtigkeit, Adressatengerechtigkeit und Teilhabegerechtigkeit leisten kann.

Bildung verstehen wir dabei als eine Hilfestellung zur Ertüchtigung des Subjekts, um im Spannungsfeld zwischen Anpassung und Eigensinn einen Weg für die mündige und verantwortliche Mitgestaltung der Digitalisierung zu finden und zu beschreiten. Um für diesen Weg ein Koordinatensystem im Sinne eines Kompasses anzubieten, verfolgen wir ein Agenturmodell Öffentlicher Wissenschaft, das einen Referenzrahmen für die Entscheidung der Subjekte für ihre Positionierung im oben genannten Spannungsfeld erschließt. Dabei nehmen wir auch die Herausforderung eines sich zunehmend inter- und intradisziplinär ausdifferenzierenden Wissenschaftssystems in den Blick. Im Modus eine Stakeholder Balancing entwickeln wir ausgehend vom Themenfeld einer innovativen Energiewende ein querschnittliches interdisziplinäres Forschungsnetzwerk, um einen Beitrag zur Auflösung vermeidbarer Widersprüche wissenschaftlicher Zugänge zu gesellschaftlich relevanten Fragestellungen und Forschungsfeldern zu leisten.

Das in diesem Beitrag skizzierte Forschungsprogramm erfordert in unserem Verständnis eine Kontextualisierung. Darunter verstehen wir die Einbettung unserer Forschungsfragen und methodischen Zugänge in konkrete Praxisfelder der Bildungs-, Interaktions- und Forschungswirklichkeit in wissenschaftlichen und außerwissenschaftlichen Öffentlichkeiten. Unser Forschungsverständnis leitet sich demnach aus der Annahme ab, das wir nur solche Phänomene, Wechselbeziehungen und Wirkweisen erforschen können, die in der konkreten Lebens- und Arbeitswelt stattfinden. Kompetenzen für die digitale Arbeitswelt sind somit auch Kompetenzen, die uns als forschende Subjekte ermöglichen, relevante Erkenntnisse für die Mitgestaltung der Digitalisierung zu gewinnen.

Danksagung

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt „Kompetenzen für die digitale Arbeitswelt (KoDiA) – Ertüchtigung zur Digitalisierung“].

Litertur

[1] B. Aulenbacher, M. Burawoy, K. Dörre und J. Sittel, Sociology and the Public in the Discourse of Crisis. Working Paper der Kollegforscher_innengruppe Postwachstumsgesellschaft, Jena, 2017.

[2] D. Baecker, „Wie verändert die Digitalisierung unser Denken und unseren Umgang mit der Welt? Ausgangspunkte einer Theorie der Digitalisierung,“ in *Handel 4.0: Die Digitalisierung des Handels – Strategien, Technologien, Transformation*, R. /. L. B. (. GLÄß, Hrsg., Berlin und Heidelberg, Springer-Verlag, 2017, pp. 3 - 24.

[3] „Coronafolgen bekämpfen, Wohlstand sichern, Zukunftsfähigkeit stärken,“ Berlin, 2020.

[4] B. C. I. 2, „Konzept für das Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr (dtec.bw),“ Berlin, 2020.

[5] M. Schulz und A. Neusius, *Forschungsantrag für das dtec.bw-Forschungsprojekt „Kompetenzen für die digitale Arbeitswelt (KoDiA): Ertüchtigung zur Digitalisierung.,* Hamburg, 2020.

[6] M. Schulz und A. Neusius, „Brauchen wir eine öffentliche Pädagogik? Zur Einführung in die Reihe. Einführung in die Dissertationsschrift von Hendrik Hoffmann,“ in *Sicherheit durch Kompetenzorientierung – Ein ressortgemeinsames Bildungskonzept für Einsatzkräfte.*, Bielefeld, wbv-Verlag, 2017, pp. 23 - 32.

[7] T. DeCesare, „The Lippmann-Dewey-“Debate” revisited: The problem of knowledge and the role of experts in modern democratic theory.,“ *Philosophical studies in education,* Bd. 43, pp. 106 - 116, 2012.

[8] J. Schlicht, *Konzept für ein Einzelprojekt im dtec.bw Forschungsprojekt KoDiA im Arbeitspaket 3, Teilprojekt 3.1 Inno-Lab BBEW – Berufliche Bildung für eine innovative Energiewende,* Freiburg, 2022.

[9] B. f. S.-. u. B. d. F. u. H. Hamburg, Hrsg., *Hamburgisches Schulgesetz (HmbSG) vom 16. April 1997, zuletzt geändert am 11. Mai 2021,* Hamburg, (1997) 2021.

[10] K. Hoolzkamp, „Was heißt "Psychologie vom Subjektstandpunkt"? Überlegungen zu subjektwissenschaftlicher Theorienbildung,“ *Journal für Psychologie,* pp. 66 - 75, 1993.

[11] M. Schulz, A. Neusius, K. Wirth und M. Hartung, Rahmenkonzept für handlungsorientierte technologiegestützte Bildungsangebote der

Berufsförderungswerke Deutschlands. Abschlussbericht zum Forschungsprojekt, Hamburg, 2007.

[12] M. Schulz, „Fernausbildung verbindet… – Technologiegestützte Bildung im Spannungsfeld von Arbeiten und Lernen, Individuum und Gesellschaft,“ in *Fernausbildung fair-netzt alle… – Zum aktuellen Stand aus Forschung und Praxis der technologiegestützten Aus-, Fort- und Weiterbildung. Tagungsband zum 3. Fernausbildungskongress der Bundeswehr*, M. Schulz und A. Neusius, Hrsg., Augsburg, Ziel-Verlag, 2008, pp. 9 - 66.

[13] M. Schulz, „Fernausbildung ist mehr… – Auf dem Weg vom technologischen Potenzial zur didaktischen Innovation,“ in *Fernausbildung ist mehr… – Auf dem Weg vom technologischen Potenzial zur didaktischen Innovation*, M. Schulz und H. Glump, Hrsg., Augsburg, Ziel-Verlag, 2005, pp. 10 - 37.

[14] M. Schulz, „Fernausbildung geht weiter ... – Grundsätzliche Überlegungen und aktuelle Entwicklungen in Theorie und Praxis,“ in *Fernausbildung geht weiter… – Neue Beiträge zur Weiterentwicklung technologiegestützter Bildung aus pädagogisch-didaktischer Perspektive*, M. Schulz, H. Breyer und A. Neusius, Hrsg., Augsburg, Ziel-Verlag, 2006, pp. 9 - 46.

[15] Kultusministerkonferenz, „Bildung in der digitalen Welt. Strategie für Schule und berufliche Bildung.,“ Berlin, 2017.

[16] „Dagstuhl-Erklärung - Bildung in der digitalen vernetzten Welt. Eine gemeinsame Erklärung der Teilnehmerinnen und Teilnehmer des Seminars auf Schloss Dagstuhl.,“ Berlin, 2016.

[17] T. Brinda, N. Brüggen, I. Diethelm, T. Knaus, S. Kommer, C. Kopf, P. Missomelius, R. Leschke, F. Tilemann und A. Weich, „Frankfurt-Dreieck zur Bildung in der digital vernetzten Welt- Ein interdisziplinäres Modell.,“ Frankfurt, 2019.

[18] A.-K. Meßmer, A. Sängerlauf und L. Schulz, „„Quelle: Internet?“ – Digital Nachrichten- und Informationskompetenzen der deutschen Bevölkerung im Test,“ 2021.

[19] OECD, „Are 15-year-olds prepared to deal with fake news and misinformation? Programme for International Student Assessment.,“ 2021.

[20] J. Bortz und N. Döring, Forschungsmethoden und Evaluation in den Human- und Sozialwissenschaften, Berlin und Heidelberg: Springer, 2016.

[21] J. A. Schülein und S. Reitze, Wissenschaftstheorie für Einsteiger. 5., aktualisierte Auflage., Wien: facultas-Verlag, 2021.

[22] M. Burawoy, Public Sociology. Öffentliche Soziologie gegen Marktfundamentalismus und soziale Ungleichheit, Weinheim und Basel: Beltz-Verlag, 2015.

[23] O. Neun, „„Public Sociology“ und „Public Understanding of Science“ (PUS) bzw. „Medialisierung“ der Wissenschaft. Zwei Paradigmen der Wissenschaftskommunikation im Vergleich,“ in *Knowledge in Action. Neue Formen der Kommunikation in der Wissensgesellschaft*, E. /. W. R. Lettkemann und H. Knoblauch, Hrsg., Wiesbaden, Springer Fachmedien GmbH, 2018, pp. 3 - 19.

[24] U. Metschl, „Wissenschaft als öffentliche Vernunft,“ in *Vom Wert der Wissenschaft und vom Nutzen der Forschung. Zur gesellschaftlichen Rolle akademischer Wissenschaft*, U. Metschl, Hrsg., Wiesbaden, Springer Fachmedien GmbH, 2016, pp. 143 - 201.

[25] N. Luhmann, Gleichzeitigkeit und Synchronisation. Soziologische Aufklärung 5. Konstruktivistische Perspektiven, Opladen: Westdeutscher Verlag, 1990, p. 95 – 130.

[26] M. Weisband, „Problem false balance: Journalisten sollen einordnen,“ *Deutschlandfunk Archiv.,* 2021.

[27] N. Rescher, „Die Fragmentierung der gegenwärtigen Philosophie am Beispiel der Philosophiegeschichte,“ *DEUTSCHE ZEITSCHRIFT FÜR PHILOSOPHIE,* Bde. %1 von %2Band 66, Heft 6, pp. 747 - 763, 2018.

[28] „google,“ [Online]. Available: www.google.de. [Zugriff am 10. Dezember 2019].

[29] M. Master, Zweites Musterbuch, Hamburg: Musterverlag, 2019.

[30] M. Mustermann, Musterbuch für Literaturverzeichnis, Hamburg: Musterverlag, 2019.

Chancen von Digitalisierung und KI in der Beruflichen Bildung nutzen - Lernende als Subjekte innerhalb des Lernprozesses wertschätzen

Prof. Dr. Michael Heister
Abteilung 4 / Bundesinstitut für Berufsbildung/ Abteilungsleiter
Bonn
heister@bibb.de

Prof. Dr. Stefan Pickl
Institut für Theoretische Informatik, Mathematik und Operations Research / Universität der Bundeswehr München
München
stefan.pickl@unibw.de

***Kurzfassung* – Die rasant ansteigende Digitalisierung hat in den vergangenen 10 Jahren zu erheblichen Ängsten in der Gesellschaft geführt. Zunächst ging es um den möglichen Verlust vieler Arbeitsplätze und Massenarbeitslosigkeit, anschließend um Horrorvisionen einer den Menschen dominierenden künstlichen Intelligenz. Diese extremen Ängste werden aktuell mehr und mehr durch realistischere Einschätzungen verdrängt. Ziel ist der digital mündige Bürger, der sich einerseits der Gefahren der Digitalisierung bewusst ist (z.B. Datensicherheit) und andererseits die Chancen (z.B. individuell zugeschnittene Angebote) nutzen kann.**

Für die berufliche Bildung und auch alle anderen Bildungsbereiche bedeutet dies, dass Lernende einen hohen Autonomiegrad erhalten, während Lehrende mehr und mehr die Rolle eines Lernbegleiters oder Lerncoaches erhalten. Diese seit einigen Jahren mehr und mehr umgesetzte Rollenzuweisung wird unterstützt durch zahlreiche neue technologische Möglichkeiten, die von KI-gestützten, stärker individualisierten Lernangeboten über digitale Zwillinge und bis zu Living Labs reichen.

I. Digitalisierung und KI führen zu Ängsten

Als vor rund zehn Jahren die beiden britischen Wissenschaftler Osborne und Frey eine Studie über mögliche Konsequenzen der Digitalisierung für den amerikanischen Arbeitsmarkt vorlegten - „The Future of Employment. How susceptible are jobs to computerisation?“ [1] -, war die Aufregung um mögliche Arbeitsplatzverluste groß. Für 47 % aller Jobs bestehe ein Risiko des Wegfalls, so die zentrale Aussage der beiden Wissenschaftler. Auch in Deutschland entstand eine heftige Diskussion um die mögliche Gefahr von entstehender Massenarbeitslosigkeit.

Allerdings setzte sich sehr schnell die Einsicht durch, dass dem Wegfall von Arbeitsplätzen auf der einen Seite das Entstehen neuer Tätigkeiten (z.B. die Entwicklung von Apps) sowie eine vermehrte Nachfrage nach Arbeitnehmenden (z.B. im Gesundheitssektor) auf der anderen Seite gegenüberstehen würde. Betrachtet man zudem die aktuell in Deutschland geführte Diskussion um das Problem des Fachkräftemangels in verschiedenen Branchen (z.B. Bauhauptgewerbe, Hotel- und Gaststättengewerbe) sind wir von der Gefahr einer Massenarbeitslosigkeit aufgrund zunehmender Digitalisierung weit entfernt.

In den letzten Jahren entstand eine weitere, mit Digitalisierung zusammenhängende Angst, die mit der Ausbreitung künstlicher Intelligenz zusammenhängt. Robotern werden Intelligenz und Bewusstsein zugeschrieben und das Szenario einer Überlegenheit von Maschinen über Menschen in die Diskussion gebracht. Vor dem Hintergrund des Kriegs in der Ukraine und möglicher Einätze autonomer Waffensysteme hat diese Problematik noch einmal an Bedeutung gewonnen.

Der amerikanische Roboterforscher Ronald C. Arkin hat in diesem Zusammenhang bereits 2010 folgendes geäußert: „Es geht auch darum, die Anwendungsbereiche von Robotern zu verstehen und zu beschränken. Wir müssen Regeln aufstellen, was der KI ermöglicht werden soll und was nicht.

Es wäre falsch, Roboter für alle vorstellbaren Anwendungen auch wirklich zu benutzen. Zusätzlich zur Ethik der KI selber müssen wir also sicherstellen, dass auch die Politik, Wissenschaftler, Ingenieure und Firmen diesen ethischen Richtlinien folgen und negative Effekte durch ihre Entscheidungen zu vermeiden helfen [2].“

Arkin hat einen sehr wichtigen Begriff gewählt:

Es geht um das Verstehen und damit letzt-endlich um Bildung. Alle Bildungsbereiche sind gefordert, um die mündige und verantwortliche Teilhabe und Mitgestaltung der Bürgerinnen und Bürger an der digitalen Arbeits- und Lebenswelt zu ermöglichen. Ganz im Sinne des in Deutschland viel zu wenig rezipierten Befähigungsansatzes von Amartya Sen [3], der die Verwirklichungschancen (capabilities) jedes einzelnen Menschen für die erfolgreiche Gestaltung seines Lebens in den Vordergrund stellt.

Genau dies steht auch im Mittelpunkt eines Forschungsprojektes der Bundeswehruniversität Hamburg, an dem die beiden Verfasser mit jeweils einem Team von der Universität der Bundeswehr München und dem Bundesinstitut für Berufsbildung mitwirken [4].

Dabei gilt unser Hauptaugenmerk der beruflichen Bildung und hier zunächst einmal der Erstausbildung, die an den

https://doi.org/10.24405/14571

verschiedenen Lernorten Betrieb, Berufliche Schule und zum Teil auch an Überbetrieblichen Berufs-bildungsstätten stattfindet.

II. STANDARDBERUFSPOSITION „DIGITALE ARBEITSWELT“

Wer sich mit den Themenbereichen berufliche Bildung und Digitalisierung einschließlich KI beschäftigt, kommt an einer wichtigen Veränderung im Rahmen der Ausbildungsordnungen nicht vorbei. Als für alle Ausbildungsberufe geltende sogenannte Standardberufsbildposition wurde die „Digitalisierte Arbeitswelt“ als neuer Standard aufgenommen. Er ist in allen ab dem 1. August 2021 in Kraft tretenden modernisierten und neu entwickelten anerkannten Ausbildungsberufen als Mindestanforderungen verbindlich zu verwenden und wird damit in den nächsten Jahren sowohl Einzug in alle Ausbildungsordnungen als auch den Berufsschulunterricht finden.

Stichworte, wie der Umgang mit digitalen Medien und Daten, Datensicherheit und Datenschutz, aber auch der Umgang mit der zunehmenden Informationsflut und mit „Fake News“ sind hier zu nennen. Hinzu kommen kommunikative und soziale Kompetenzen, die in der digitalen Arbeitswelt eine immer wichtigere Rolle spielen. Durch berufs- oder branchenspezifische Besonderheiten kann es in den Ordnungsverfahren zu erweiterten Inhalten bezogen auf die „Digitalisierte Arbeitswelt“ kommen. Auch das in vielen Bereichen (z.B. Instandhaltung) immer wichtiger werdende Thema KI dürfte dabei eine Rolle spielen [5].

Im Grunde kommt Digitalisierung und KI in der Berufsbildung eine doppelte Bedeutung zu: Einerseits als berufsspezifischer Ausbildungsinhalt und andererseits als Lehr-/Lernmittel/-medium, durch das ein individuelleres Lernen und die Berücksichtigung unterschiedlicher Lerntypen sowie auch Lernbarrieren ermöglicht wird. Unter Berücksichtigung beider Aspekte ergibt sich durch die Neuregelung nach unserer Ansicht in mehrfacher Hinsicht eine große Chance, die beherzt aufgegriffen werden muss:

- Digitalisierung durchdringt alle Bereiche und sollte daher nicht als eigenes Thema sozusagen on top gesetzt werden. Vielmehr sollte es in bereits existierende Tätigkeiten und Inhalte einbezogen und damit harmonisch in die Ausbildung integriert werden.
- Die notwendigen Kenntnisse und Fähigkeiten sollten von den Auszubildenden weitgehend im Rahmen von Projekten mit einem hohen Autonomiegrad selbst erarbeitet werden. Der Lehrende tritt als Lerncoach in den Hintergrund. So kann insbesondere auch der kritische Umgang mit Digitalisierung besser gelernt werden als durch den Erwerb sogenannter Computerführerscheine.
- Zahlreiche mit der Digitalisierung einhergehende technische Möglichkeiten (Filme auf dem Smartphone, Digitale Zwillinge, Living Labs) bieten den Lernenden Möglichkeiten, um sich Lehrinhalte mit Unterstützung durch den Lerncoach selber zu erarbeiten.

Diese drei genannten Aspekte können und sollten nun einzeln in verschiedenen Lernumgebungen erprobt und weiterentwickelt werden. Im Rahmen des aktuellen dtec- Projektes KoDia könnte das Konzept des Living Lab als einen möglichen integrierenden Rahmen für alle drei Bereiche erstmals angewendet und untersucht werden.

III. III. KODIA UND INTEGRATIVER KOMPETENZERWERB

Das Forschungsprojekt KoDiA steht für den integrativen Kompetenzerwerb für die digitale Arbeits- und Lebenswelt. Eine Möglichkeit diesen besonderen Kompetenzerwerb im Rahmen eines „Digitalen Bildungserwerbs“ nun „praxisnah“, „real“ und zugleich „virtuell unterstützt/begleitend“ umzusetzen ist das begleitende Konzept von sogenannten Living Labs (LL), die sich durch diese Eigenschaften auszeichnen. Das Konzept steht für ein interaktives/ agiles Stakeholdermanagement, das integrierende Plattformen zunächst initiiert, die dann in einer Living Lab Umgebung in einem adaptiven Sinne zukunftsweisend zusammengeführt werden. „Living“ weist insbesondere auf zwei Aspekte hin:

Einmal auf die praxisnahe Lebenswelt („Leben“) aber auch als Adjektiv „lebend“ im Sinne eines pädagogischen dynamischen Entwicklungsprozesses.

Durch diese Beschreibung wird deutlich, dass damit ein besonderes **Subjekt-Objekt Verhältnis** beschrieben wird, das im Folgenden im Kontext der beteiligten Schulen näher ausgeführt werden soll.

Herausforderungen sind hierbei die unterschiedlichen Bildungsvoraussetzungen, inklusive der Unterschiede des jeweiligen Lehrangebotes und der einzelnen Ausbildungsmöglichkeit, als auch die verschiedenen vorhandenen Digitalisierungsgrade in den beteiligten Schulen.

Das Bundesministerium für Wirtschaft und Klimaschutznutzt derzeit einen ähnlichen Ansatz, der sich speziell auf die Erprobung digitaler Innovationen als LL-Umgebung konzentriert.

Schulische Lernsituationen zeichnen sich häufig durch den Umgang mit einzelnen Texten, Werken und begleitenden unterschiedlichen Quellen aus. Die hier beschriebene KoDia-Forschungs-Kooperation fokussiert im Rahmen des dtec-Projektes speziell auf mögliche KI-basierte Digitalisierungsbemühungen.

In diesem Kontext kommt auch der möglichen zusätzlichen Einbettung von AR/VR-Anteilen eine besondere Bedeutung zu. Durch die Integration von AR/VR wird u.a. ein besonderer Schwerpunkt auf den Ausbau der visuellen Komponente gesetzt, welcher adaptierbar ist und einen zusätzlichen Ansatz des Lernens darstellt.

Exemplarisch wird dieser Ansatz nun an einem literaturwissenschaftlichen Begleitprojekt erprobt, bei dem das Werk mit dem Leben des Autors „digital verbunden“ wird.

Dabei werden Umweltbedingungen, Gebäudeeigenschaften, Architekturumgebungen ebenso einbezogen wie Sekundärliteratur und Begleittexte:

Damit soll nicht nur eine Digitalisierung abgestrebt werden, sondern es sollen KI-unterstützt „Stimmungen“ beim Lernenden erzeugt werden. Das Beispiel macht deutlich, dass der Lernende nicht als reines Objekt, sondern als Subjekt in dem Reallabor anzusehen ist.

Diese spezielle Subjekt-Beziehung, die sich auch in dem Namen „Reallabor“ ausdrückt, wird durch die besondere Kooperation zwischen den Wissenschaftlern und den beteiligten Schulen beschriebenen. Das zugrundeliegende

Living Lab zeichnet sich durch das „wechselseitige“ Lernen als auch durch das dynamische experimentelle Umfeld aus.

IV. Strategieentwicklung durch Aktion

Das gemeinsame Vorgehen bzgl. der beteiligten Schulen zeichnet sich nun durch die folgenden drei Aspekte aus:

- Experimentelles Agieren in realen Kontexten (jedoch unterschiedlichen Schulumgebungen)
- Dynamische Partizipieren im Sinne des Lernenden als Subjekt
- Living Labs als moderne Plattform, um ein gemeinsames Erarbeiten von Wissen zu ermöglichen

Besondere Herausforderung ist in dem Projekt die Berücksichtigung des jeweiligen Digitalisierungsgrades, der mit den einzelnen sozialen Kontexten und unterschiedlichen didaktischen Rahmenbedingungen verbunden werden soll.

In der Literatur zu Living Labs wird oft von „Strategieentwicklung durch Aktion“ gesprochen. Dieses aktive Element in der entsprechenden Aktion soll durch die Digitalisierung besonders gefördert werden. Um in dem herangezogenen Literaturbeispiel zu bleiben:

Ich gehe nicht einfach nur durch das Haus in dem Buch, sondern ich „entdecke“ und „erschließe“ mir etwas in einem aktiven Sinne. Es geht daher auch nicht nur um Wissensaneignung, sondern um ein sich strategisches Erschließen.

Darüber hinaus ermöglicht man jedem Individuum speziell auf seine eigenen Interessen einzugehen, beispielsweise bei der Auswahl bzw. der Reihenfolge der Räumlichkeiten, die im Haus betreten werden.

V. Kollaborative Lernumgebung - didaktische Symbiose

Es kommt damit zu einer Verschmelzung von Lernenden und Lernumgebungen als eine didaktische Symbiose. Dieser didaktische Prozess überträgt sich auf die beteiligte Lerngruppe, so dass das Living Lab für eine kollaborative Lernumgebung steht.

Die Möglichkeit des gegenseitigen Austausches innerhalb des Living Lab fördert dies in besonderem Maße.

Ursprünglich wurde der Begriff des „lebenden Labors“ Ende der 90er Jahre am Massachusetts Institute of Technology (MIT) kreiert. Fast 10 Jahre später wurde im Rahmen der Lissabon-Strategie ein besonderer Fokus auf die Forschung im LL-Kontext gelegt:

Während der finnischen Präsidentschaft in der Europäischen Gemeinschaft wurde die Initiative „Living Lab Europe“ entwickelt. Parallel hierzu wurde ein europäisches Netzwerk von Living Lab mit der Bezeichnung „European Network of Living Labs“ kreiert.

Mit dem hier beschriebenen Projekt könnte nun ein „Hamburg Network of Living Labs“ als reiner Arbeitstitel entwickelt werden. Ziel ist es dabei, offene Innovationen zu fördern, (vorhandene) Netzwerke zu teilen und Benutzer von Anfang an einzubeziehen.

Diese drei Aspekte ergänzen sich zu den oben genannten drei Punkten, die im Zentrum des Forschungsprojektes stehen. Damit steht das Projekt für einen dynamischen Forschungs- und gleichzeitig stattfindenden Innovationsprozess.

VI. Wissenschaftszentrum der neuen Generation

In [6] findet man die Aussage, dass Living Labs speziell dafür stehen, dass dieser Ansatz die Zusammenarbeit zwischen heterogenen Profilen von Menschen anregen, um unerwartete Entdeckungen zu entwickeln.

Es ermöglicht einer Bevölkerung daher, Veränderungen in unserer Gesellschaft zu beeinflussen und die sozialen, technologischen und wirtschaftlichen Probleme zu verstehen

Ob ein Living Lab auch für ein neues Paradigma steht, sei hier offengelassen. Wichtig ist jedoch, dass es sich anbieten könnte, ein "Wissenschaftszentrums der neuen Generation" vorzubereiten.

Dieses Zentrum soll Chancen von Digitalisierung und KI in der Beruflichen Bildung nutzen und gleichzeitig Lernende als Subjekte innerhalb des Lernprozesses wertschätzen.

Danksagung

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [KoDiA]

Literatur

[1] C. Frey and M. Osborne, The Future of Employment. How Susceptible Are Jobs to Computerisation, Oxford 2013, 2013.

[2] R. C. Arkin, "Wir sollten kein Monopol auf ethisches Handeln haben," 2010. [Online]. Available: https://www.theeuropean.de/ronald-c-arkin/136-ethik-fuer-kuenstliche-intelligenzen.

[3] A. Sen, "Human Rights and Capabilities," *Journal of Human Development, vgl. 6, ,* p. 151 – 166, 2005.

[4] BIBB-Pressestelle, "www.bibb.de," 2022. [Online]. Available: www.bibb.de/de/pressemitteilung_151515.php.

[5] E. /. B. W. /. H. M. e. a. (. André, "Kompetenzentwicklung für Künstliche Intelligenz – Veränderungen, Bedarfe und Handlungsoptionen.," 2021.

[6] Wikipedia, "Living lab," 08 09 2022. [Online]. Available: https://en.wikipedia.org/wiki/Living_lab.

Supporting Digitization by Learning Process Consulting

Juliana Schlicht*
University of Education Freiburg,
Institute of Business Education and Management Training
Freiburg, Germany
*juliana.schlicht@ph-freiburg.de

***Abstract* – Neither the digitization of existing business processes nor the development of new digital business models can take place without human interventions. They must be accompanied by effective learning, which needs to be supported systematically. This article introduces the concept of learning process consulting, which is developed on the basis of psychological and educational theories and tested in an energy company. Learning process consulting is the "didactic joint" in digitization projects. In terms of personnel, it is realized by learning process consultants for whom a role with concrete tasks is described here. These consultants ensure sequences of reflective communication and cooperation. Furthermore, they enable and monitor the participation of employees and managers (non-computer scientists) – with the aim of generating transparency, acceptance and trained system users. The concept provides starting points for further educational and informatics research and applications, e.g. regarding the design of technical aids for data-based learning process consulting.**

Keyword – Reflective communication and cooperation, human learning, participative system development, process consulting

I. Design and Testing Context

Digitization projects often aim at using IT solutions for restructuring the cooperation in business processes [1]. Thus, acceptance and competent handling of IT solutions are crucial [2]. In order to meet these criteria, it is necessary to initiate and support learning processes. Hereafter a concept for learning process consulting is depicted. It is based on psychological and education theories, and was tested in a digitization project in a company of the European gas transport system [3]. The project included the design and implementation of a ticket system that could be used to deal with complex complaints from business partners (e.g. customers, service providers, authorities) across spatial distances as well as department and discipline boundaries. Learning process consultants guided the digitization project by enhancing learning through didactically sequenced communication and cooperation. In the following the conceptual fundamentals of this specific consulting role as well as some project results are outlined.[1]

II. Tasks of Learning Process Consultants

In the energy company involved, it has been evident that learning in digitization projects can be systematically supported when consulting is oriented on scientific approaches to subject-, team- and system-oriented business process management and business education [3], [6], [7], on concrete business situations, and on the personality of the learners [9]. These scientific, situation and personality principles provide a framework for a concept of consulting that is focused on the learning processes (see FIGURE 1).

Supporting learning processes includes recording, analyzing, designing and testing reflective communication and cooperation – with digital and non-digital media – in order to reduce complexity and acquire previously identified development needs [3]. Accordingly, learning process consultants accomplish several tasks:

- They carry out target group analyses focusing on cognitive, motivational and emotional learning premises, social structures in business situations as well as on technical working conditions (e.g. with the help of online-surveys, interviews, social network analyses [10], and typifications [11]). Additionally, they evaluate project results from the point of view of both the individual as well as the collective development [12]. Beside data collection and data analyses it includes a didactical preparation of empirical results. Thus, findings are transformed into learning objects.
- Furthermore, they consider the participatory character of system development [6]. That means, they involve the prospective system's users (non-computer scientists) during the process of IT development as "co-designers" [13] in order to generate transparency about the goals, conditions and the process of digitization. While teaching them the acceptance of IT solutions is promoted simultaneously. Even employees without management responsibility are involved in the

[1] The paper was presented on the 15th International Conference on Wirtschaftsinformatik, March 08-11, 2020, Potsdam, Germany. Here, it is republished based of research results of the author's habilitation project [3], which was realized in the field of Business Education and Management Training (Wirtschaftspädagogik) at the interface to Business Administration (Betriebswirtschaftslehre) and Business Informatics (Wirtschaftsinformatik). The case study in the energy company lasted 2.5 years (2012–2015). It was based on a new design-oriented methodological approach to "analytical-constructive modelling" [3]. This approach allows to interlink concepts of different disciplines addressing empirically founded learning as well as reflective communication and cooperation in and between large process teams ($n \geqslant 20$), e.g. concepts of cooperative learning [4], subject-oriented "agile" process management [5, 6], team development [7], and "mass communication" [8] together with combinations of research methods for qualitative and quantitative data analyses. The approach is also used in a recently launched project dealing with vocational training for an innovative energy transition.

https://doi.org/10.24405/14572

development process, including the decision making on digitization, e.g. in meetings and workshops with a top-down-bottom-up decision-making sequence [6].

- Additionally, they ask prospective system's users to engage with the learning objects (findings) in a communicative and cooperative way enabling interdisciplinary problem-based learning [14]. Above all, they initiate and support the learning while all project members involved are planning and conducting the digitization, and then while using the project results for daily business and process management.

In the energy company it has been shown that current learning (in the digitization project) and future learning (in the digitalized business processes) can be supported when communication and cooperation is realized in the sequence of "Experience – Abstract – Reflect & Design – Test" (see FIGURE 1).

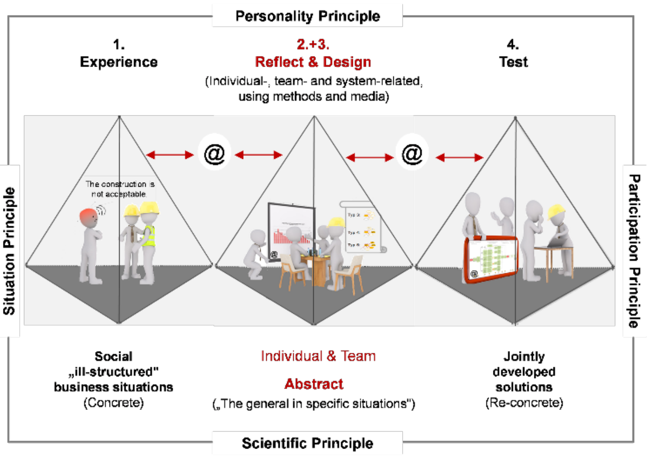


FIGURE 1: SEQUENCING LEARNING AND PRINCIPLES OF LEARNING PROCESS CONSULTING [3].

This sequencing idea is based on the psychologically founded approach of Achtenhagen et al., who address the microsequencing of teaching-learning processes in business contexts [15]. The authors summarize their idea in the established wording "Concrete – Abstract – Re-concrete" and emphasize that an individual understanding of concepts and the collective negotiation of meanings can thus be realized (symbolized in FIGURE 1 as a gray marked foundation). Moreover, Euler's psychologically based sequencing approach is taken up [4]. He states that the development of communication and cooperation skills (including skills for social interaction using digital tools) can be promoted when the individual learning process is embedded in concrete business situations and when the teamwork is realized with regard to the triad "Experience – Reflect & Design – Test" (symbolized as social space in FIGURE 1). Both approaches are interconnected as explained below:

1. The starting and reference point for learning are concrete (social) business situations which are experienced by employees and managers and are perceived as "ill-structured" (complex) [16]. FIGURE 1 shows an example situation in which a business partner articulates his dissatisfaction with a construction project and in which the complaint is dealt within interdisciplinary teamwork by businessmen and engineers.

2. With reference to the learning premises and working conditions of the target group (prospective system's users), the experienced situations are reflected individually and collectively (e.g. in meetings). These activities aim at identifying the general and characteristic elements of specific situations. On top of that, these seek to describe the development needs for employees and managers, for teams and for the company, e.g. by diagrams, networks and typologies (abstract).

3. On the basis of experiences (step 1) and with regard to the development goals possible courses of action are discussed from the point of view of the persons involved and of various professions. Decisions on digitization are made in a participatory way, e.g. to process complaints more effectively by the team in the future. Accordingly, new IT solutions (prototypes with model character) are designed which enable reflective communication and cooperation within and between teams as well as across spatial distances (symbolized by "@" in FIGURE 1).

4. The jointly developed solutions are tested in a "protective space" (e.g. in pilot tests). After a successful trial run they are implemented in operational practice (re-concrete).

III. PRACTICAL IMPLEMENTATION AND OUTLOOK

In the digitization project of the energy company, two pedagogically trained learning process consultants supported a group of 20 employees (non-computer scientists) interacting with one business process manager and one IT specialist developing a ticket system which facilitates communication, cooperation and learning of 270 employees in daily business. The evaluation results [3] lead to the conclusion that it is possible to gain insights into how learning process consulting can and should be realized by conducting a participative research approach. Additionally, the project has shown that in a company where such role has not been established, employees and executives need to be supported – at least during the initial stages – by pedagogically trained personnel. It remains to be examined whether and how IT-consultants can be prepared effectively as learning process consultants. Furthermore, it should be investigated to what extent consulting teams need to consist of experts from different disciplines working together with distributed roles and different work focuses (e.g. on didactical support of individual and collective learning processes, on the management of large interdisciplinary process teams, on participative system development). Furthermore, it should be explored which kind of technical aids could support the data-based learning process consulting in other industries, business and IT contexts. Finally, the methodological approach to "analytical-constructive modelling" [3], which was used to design the new consultant role, should be reflected from a Business Informatics perspective. Could the presented educationally accentuated approach help to overcome limitations in "agile" software development-methods (e.g. scrum, kanban) which were recently stated [17], [18]? At least, this requires a broad interdisciplinary discussion as well as cooperations between actors from Wirtschaftspädagogik and Wirtschaftsinformatik. This paper aims at providing an impulse for that.

REFERENCES

[1] C. Loebbecke, A. Picot, Reflections on societal and business model transformation arising from digitization and big data analytics: A research agenda. The Journal of Strategic Information Systems 24, 149–157, 2015.

[2] T. Müllerleile, Prozessakzeptanz. Theoretische und empirische Untersuchung der Akzeptanz und Ablehnung betrieblicher Prozesse, Wiesbaden: Springer Gabler, 2019.

[3] J. Schlicht, Kommunikation und Kooperation in Geschäftsprozessen. Modellierung aus pädagogischer, ökonomischer und informationstechnischer Perspektive, Bielefeld: W. Bertelsmann Verlag, 2019.

[4] D. Euler, Methoden und Prinzipien zur Förderung von Sozialkompetenzen im Rahmen des kooperativen Lernens, In: D. Euler, G. Pätzold, S. Walzik, (eds.) Kooperatives Lernen in der beruflichen Bildung, pp. 33–46, Stuttgart: Steiner, 2007.

[5] K. Beck et al., Manifesto for Agile Software Development, http://www.agilemanifesto.org [Accessed on 31 August 2022].

[6] A. Fleischmann, W. Schmidt, C. Stary, M. Augl, Agiles Prozessmanagement mittels Subjektorientierung. HMD 50, 64–76, 2013.

[7] M. Gaitanides, Prozessorganisation. Entwicklung, Ansätze und Programme des Manage¬ments von Geschäftsprozessen, München: Franz Vahlen, 2012.

[8] K. Beck, Kommunikationswissenschaft, München: UVK Verlagsgesellschaft, 2015.

[9] T. Tramm, L. Reetz, Berufliche Curriculumentwicklung zwischen Persönlichkeits-, Situations- und Wissenschaftsbezug. In: R. Nickolaus, G. Pätzold, H. Reinisch, T. Tramm (eds.) Handbuch Berufs- und Wirtschaftspädagogik, pp. 220–226, Bad Heilbrunn: Klinkhardt, 2010.

[10] J. Raab, Netzwerke und Netzwerkanalyse in der Organisationsforschung. In: C. Stegbauer, R. Häußling (eds.) Handbuch Netzwerkforschung, pp. 575–586, Wiesbaden: VS Verlag für Sozial¬wissenschaften, 2010.

[11] U. Kuckartz, Typenbildung. In: G. Mey, K. Mruck (eds.) Handbuch Qualitative Forschung in der Psychologie, pp. 553–568, Wiesbaden: VS Verlag für Sozialwissenschaften, 2010.

[12] F. Klauser, H.-O. Kim, Analyse der Zielgruppen für IMPULS EC. Konzeption, Befunde und Diskussion. IMPULS EC Research Report, 5, Osnabrück, 2003.

[13] S. Weber, Design Experiment. In: F.-J. Kaiser, G. Pätzold (eds.) Wörterbuch Berufs- und Wirtschaftspädagogik, pp. 211–213, Bad Heilbrunn: Klinkhardt, 2006.

[14] M. Brassler, J. Dettmers, Interdisziplinäres Problembasiertes Lernen – Kompetenzen fördern, Zukunft gestalten. Zeitschrift für Hochschulentwicklung (ZFHE) 11, 17–37, 2016.

[15] F. Achtenhagen, E.G. John, P. Preiß, T. Tramm, H. Seemann-Weymar, A. Schunck, Lernhandeln in komplexen Situationen – Neue Konzepte der betriebswirtschaftlichen Ausbildung, Wiesbaden: Gabler, 1992.

[16] D. Dörner, Die Logik des Misslingens. Strategisches Denken in komplexen Situationen, Reinbek: Rowohlt Taschenbuch Verlag, 2011.

[17] K. Prott, Maximale Agilität mit Softwareentwicklung 4.0: Zusammenspiel von Agilität, DevOps, Microservices und Cloud: Rückbesinnung aufs Wesentliche. OBJEKTspektrum: Moderne Vorgehensmodelle – Was auf Scrum und Kanban folgt, 01/2020, 10–14, 2020.

[18] T. Glaser, Renaissance statt Revolution – zurück in die Vernunft: Rückbesinnung aufs Wesentliche. OBJEKTspektrum: Moderne Vorgehensmodelle – Was auf Scrum und Kanban folgt, 01/2020, 28–32, 2020.

Kapitel IV

Organisation – Personal – Arbeit – Leadership (OPAL)

mit Beiträgen von

German Institute for Economic Research (DIW Berlin)

Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg

Northern Business School

Q Agentur für Forschung

Universität der Bundeswehr München

vhw – Bundesverband Wohnen und Stadtentwicklung

Vorwort zum dtec.bw-Dachprojekt „Organisation – Personal – Arbeit – Leadership (OPAL)”

Digitalisierung meint nicht nur Technik, sondern impliziert soziale Einbettung. Es bedarf der Organisation ebenso wie der Investition in Bildung, der Entwicklung von Personal, der Personalführung etc., um digitale Technik sozial und ökonomisch zweckmäßig nutzen und (weiter)entwickeln zu können. Die Forschungs- und Entwicklungsziele im Dachprojekt „Organisation – Personal – Arbeit – Leadership“ (OPAL) sind entsprechend vielfältig und werden aus Perspektive verschiedener geistes-, sozial- und wirtschaftswissenschaftlicher Disziplinen verfolgt, wobei Inter- und Transdisziplinarität zu den technischen Fächern eine Gemeinsamkeit bildet.

Die unter dem Dach OPAL versammelten Projekte erforschen Digitalisierung in unterschiedlichen Kontexten wie der privatwirtschaftlichen Produktion und Dienstleistung, öffentlichen Organisationen, im militärischen Bereich oder in sozialen und kulturellen Einrichtungen. Es werden verschiedene Funktionen wie Bildung und Beruflichkeit, Führung und Organisation am Beispiel von Firmen, Plattformen, Verwaltungen oder Bildungseinrichtungen im urbanen oder ländlichen Raum thematisiert. Ziele sind sowohl die Weiterentwicklung von Theorien und die Gewinnung empirischer Erkenntnisse als auch die praktische Erprobung von Konzepten, Programmen und Routinen. Ferner ist unter dem Dachprojekt mit dem „Linked Employee-Employer-Survey“ des sozio-oekonomischen Panels (SOEP) ein Infrastrukturprojekt der sozialwissenschaftlichen Forschung angesiedelt, das grundlegende Informationen für die nachhaltige Forschung zum digitalen Wandel in der Arbeits- und Lebenswelt zur Verfügung stellt.

Trotz der externen Widrigkeiten durch Pandemie und Krieg, also nicht der in projektförmiger Forschung mehr oder weniger erwartbaren Anfangsschwierigkeiten, kann sich der Forschungsschwerpunkt hier bereits in seiner ganzen Breite präsentieren. Wir danken unseren Partnern in Anwendung und Forschung, die mit uns Hürden überwunden und diese frühen Publikationen möglich gemacht haben.

Hamburg, im November 2022

Wenzel Matiaske

Dachprojektleiter „Organisation – Personal – Arbeit – Leadership“

DigiTaKS*-Digitale Schlüsselkompetenzen für Studium und Beruf

S. Schmidt-Lauff*, J. Schwarz, T. Rosemann, M. Rathmann, J. Schiller
Professur für Weiterbildung und lebenslanges Lernen
Hamburg, Deutschland
*digitaks@hsu-hh.de

***Abstract* – Die Digitalisierung der Gesellschaft bringt immer wieder Innovationen hervor, die zugleich auch neue Fragen aufwerfen. Es bedarf der Aneignung umfassenden Wissens über diese Prozesse, weitreichender Kompetenzen im praktischen Umgang mit ihnen und zugleich einer kontinuierlichen (Lern-)Bereitschaft, um auf zukünftige Chancen und Herausforderungen ‚digital kompetent' reagieren zu können. Der Erwerb und Ausbau digitaler Kompetenzen wird daher zu einer Querschnittsaufgabe des gesamten Bildungssystems, wobei den Hochschulen insbesondere bei der Vermittlung höherwertiger *transformativer digitaler Kompetenzen* eine entscheidende Rolle zukommt. Das von dtec.bw geförderte Forschungs- und Entwicklungsprojekt DigiTaKS* setzt hier an, indem es ein *Modell zur transformativen digitalen Kompetenzentwicklung Studierender* – bestehend aus einem Hard- und Softwarepaket, Instrumentarien zur Kompetenzdiagnose und –entwicklung sowie barrierefreien, kollaborativen Lehr- und Lernressourcen – für die Hochschule entwickelt und erprobt. Die längsschnittlich-begleitende, multimethodisch angelegte Forschung im Rahmen des Projektes zeigt in ersten Teilergebnissen kontextbezogene Differenzen in den Nutzungsweisen digitaler Medien auf und identifiziert Problemlösung mittels digitaler Technologien als zentrale Herausforderung in der Generation der sog. ‚digital natives'. Diese ersten Befunde bieten Impulse für die weitere Forschung und die adressatengerechte Gestaltung der Tools zur Diagnose und Weiterentwicklung digitaler transformativer Kompetenzen.**

Digitalität, transformative digitale Kompetenzen, Hochschulbildung, Professionalisierung, Lebenslanges Lernen, Erwachsenenbildung, Längsschnittuntersuchung

Nomenklatur

HSU	Helmut-Schmidt-Universität/Universität der Bundeswehr Hamburg
AP	Arbeitspaket
OER	Open Educational Ressource(s)
GeiSo	Geistes- und Sozialwissenschaften
IuK-…	Informations- und Kommunikations-…

I. Ausgangslage

Der digitale Wandel der Gesellschaft und Arbeitswelt geht mit weitreichenden und sehr grundlegenden Transformationen sozialer Strukturen und Praktiken einher. Während im öffentlichen Diskurs mit Digitalisierung zumeist nur die Ausbreitung neuer, digitaler IuK-Technologien benannt wird, wird im sozialwissenschaftlichen Fachdiskurs der Blick auf eine *Kultur der Digitalität* [1] gerichtet und damit die umfassende Transformation von Handlungs-, Kommunikations-, Selbst- und Arbeitsmöglichkeiten diskutiert [2]. Das Digitale und Analoge verschmelzen zusehends. Im Begriff der Digitalität wird dies als relationale *Konnektivität* [3] zwischen Mensch und Technik oder als *ontologische Virtualität* [4] gefasst. Digitalität eröffnet aus dieser sozio-kulturellen Sicht neue Praktiken, die ebenso identitätsbildend und handlungsleitend wie zugleich gesellschaftstransformierend wirken.

Dies betrifft in besonderer Weise das Bildungssystem, das sich erstens infrastrukturell und alltagspraktisch mit der Digitalisierung auseinandersetzen, zweitens die daraus hervorgehenden Themen (KI, autonome Systeme, Big Data, etc.) zu Inhalten und Lerngegenständen machen und drittens den Lernenden die Befähigung und Bereitschaft im Rahmen lebenslangen Lernens vermitteln soll, sich auf immer neu entstehende Chancen und Herausforderungen einzustellen [5]. Der Erwerb und kontinuierliche Ausbau digitaler Kompetenzen wird also zu einer Querschnittsaufgabe für das gesamte Bildungssystem, wobei auch die Hochschulen eine wichtige Rolle einnehmen [6], [7] – entgegen verbreiteter Vorstellungen (gerade) auch gegenüber den ‚digital natives' [8]. Im Gegensatz zum schulischen Fokus auf allgemeine und grundlegende (digitale) Kompetenzen verantworten Hochschulen eine berufsqualifizierende, wissenschaftlich-fachspezifische Ausbildung auf hohem Niveau, die auch zu Entscheidungskompetenzen und Führungsverantwortung befähigen soll. Hierfür sind höhere Niveaus digitaler Kompetenz zwingend notwendig, deren Vermittlung die Hochschulen deshalb verstärkt in den Blick nehmen müssen [9]–[11]

II. DigiTaKS* – Digitale Schlüsselkompetenzen für Studium und Beruf

Das Forschungs- und Entwicklungsprojekt *DigiTaKS* - Digitale Schlüsselkompetenzen für Studium und Beruf* setzt hier an: *DigiTaKS** zielt auf der Grundlage empirisch fundierter und interdisziplinär gewonnener Daten darauf ab, ein Modell zur Vermittlung und Aneignung transformativer digitaler Kompetenzen im Hochschulstudium zu entwickeln. Ziel ist es, Studierenden zu ermöglichen, höherwertige Kompetenzen zu erwerben, um die Potentiale der Digitalisierung umfänglich zu reflektieren und zielführend auszuschöpfen. Im Sinne transformativer digitaler Kompetenzen sollen sie digitale Räume nicht nur angemessen nutzen, sondern deren Voraussetzungen, Funktionsweisen und Wirkungen auf unterschiedlichen Ebenen differenziert reflektieren und sie auf dieser Grundlage zielführend und kreativ-innovativ gestalten können. Leistungen und Chancen ebenso wie Probleme und Risiken der Digitalität in Bildungs- und Arbeitskontexten sollen sie kritisch hinterfragen können und so entsprechende Entscheidungen

https://doi.org/10.24405/14573

zur Auswahl, zu Einsatzformen, zur Adaption oder (Weiter-) Entwicklung digitaler Technologien und Praktiken nachhaltig und zukunftsweisend treffen [12], [13]. In dem Projekt werden dafür Infrastrukturentwicklung (Hard- und Software) sowie Kompetenzdiagnostik und -entwicklung miteinander verzahnt. Als interdisziplinär ausgerichtetes Vorhaben, ist das Projekt im Kontext Bildungs- und Erziehungswissenschaft, Medienpädagogik und IT-Entwicklung/ -Support verortet und arbeitet mit verschiedenen Partnern aus Hochschule, IT, Bildung zusammen. Insbesondere Studierende nicht-technikaffiner Fachbereiche werden im Projekt als *digital change agents* adressiert, weil sie später möglicherweise Leitungs- und Führungsaufgaben in privatwirtschaftlichen, öffentlichen, zivilen und militärischen Organisationen übernehmen werden und dabei die Digitalisierung in ihren jeweiligen Handlungsfeldern entscheidend mitgestalten und zugleich als Multiplikator:innen dienen können.

III. Transformative digitale Kompetenzen

Seit einiger Zeit werden im Kontext von (Weiter-)Bildung und Lernen bildungstheoretische Grundlegungen wieder neu diskutiert, die normative und kulturelle Justierungen und deren empirische Durchmusterung zusammendenken, um zu einem zeitgemäßen Verständnis transformatorischer Bildung zu gelangen [12], [14]–[16]. Kurz gefasst geht es im Kern um Transformationen der Selbst- und Weltbeziehungen, die bei genauerem Hinsehen auf ein holistisches [13] Veränderungsgeschehen grundlegender Strukturen unseres Verhaltens, Denkens, Fühlens und damit unserer Selbstverhältnisse abheben (*meaning structures* and *meaning perspectives*; [17]). Dies muss gegenwärtig fast zwangsläufig zu Auseinandersetzungen um das *digitale Moment* und Einflüsse der Digitalität auf Selbst- und Weltverhältnisse wie auch auf Lern- und Bildungsprozesse führen. Beispielsweise geht es um eine kritische Haltung gegenüber Datafication, um eine emanzipatorische Sensibilität für konnektive Potenziale (Mensch-Technik; KI) oder um eine Austarierung digital-analoger Bildungsmöglichkeiten [18]. Transformative digitale Kompetenzen sind nicht Resultat lediglich kumulativer Lernprozesse zum Digitalen, sondern entfalten sich als bedeutsame, reflexiv wiederkehrende Prozesse wissens- und erfahrungsbedingter Modifikationen. Sie bedeuten auch Gestaltungskompetenz in der digitalen Transformation [19]. Dies ist aus unserer Sicht nicht nur zeitgemäß und nachhaltig, sondern der Komplexität, Potenzialität und Problematik des Digitalen (s.o.) auch angemessen.

Zur Vermittlung und Aneignung höherer Kompetenzniveaus werden in *DigiTaKS** dafür auf Basis des europäischen Referenzrahmens für digitale Kompetenzen DigComp 2.1. [20] und der aktuell weiterentwickelten Variante DigComp 2.2 [21] ein Diagnosetool (*ComDigiS**) sowie darauf basierend ein Kompetenztraining (*ComDigiTrainS**) entwickelt und im Hochschulkontext erprobt. Lerntheoretische Konzepte, wie das *transformative learning* [17] und das für den Bereich der beruflichen Bildung entwickelte COMET-Kompetenzmodell [22], welches ermöglicht, eine Verknüpfung zu komplexen beruflichen Lernsituationen herzustellen, werden in den entwickelten Produkten im Rahmen des Projektes berücksichtigt.

IV. Projektstruktur: Entwicklung, Forschung, Umsetzung

In *DigiTaKS** werden technische Ausstattung mit individueller Diagnose, Kompetenzentwicklung und Training verbunden:

(1) Ein *Digitales Basispaket bestehend aus Hard- und Softwaresuite*,
(2) *Instrumentarien zur digitalen Kompetenzdiagnose* (Selftest *ComDigiS**) und -entwicklung (Training *ComDigiTrainS**) sowie
(3) barrierefreie *Open Educational Ressources (OER)*.

Durch ein multimethodisches Forschungsdesign ermöglicht das Projekt die Bereitstellung empirisch fundierter Informationen über die Bedarfslage, Anforderungen und den faktischen Stand digitaler Kompetenzen der Studierendengeneration ebenso wie zu den umsetzungspraktischen Herausforderungen und Hürden von Digitalisierung in der Hochschulbildung.

Auf der Grundlage begleitender längsschnittlicher und multimethodischer Nutzungs- und Wirkungsforschung werden drei Studierendenjahrgänge (HSU) der Studiengänge Bildungs- und Erziehungswissenschaft, Geschichte und Psychologie forschend begleitet. Zur Analyse, Diagnose und Entwicklung transformativer digitaler Kompetenzen bei Studierenden arbeiten dazu im Rahmen von *DigiTaKS** insgesamt fünf ineinandergreifende Arbeitspakete (AP) mit verschiedenen Schwerpunkten:

Das AP1 ***‚Digitales Arbeiten und Lernen im Studium‘*** (HSU) fokussiert alltägliche Lern- und Arbeitspraktiken im Kontext eines digitalisierten Studiums als eine komplexe Gelegenheitsstruktur für den Erwerb transformativer digitaler Kompetenzen, wobei intentionale wie inzidentelle, fachliche wie überfachliche, hochschulseitig wie selbstorganisierte Lernprozesse in den Blick genommen werden. Einen besonderen thematischen Schwerpunkt bilden zudem Strategien und Wirkungen der Lern- und Arbeitsorganisation in analogen und digitalen Settings. Auf Basis einer initialen Bedarfs- und Anforderungsanalyse (Mai 2021–Oktober 2021; vgl. [23]) erfolgt im Rahmen des Projektes eine längsschnittliche Nutzungs- und Wirkungsstudie zur Analyse von Vermittlung und Aneignung transformativer digitaler Kompetenzen Studierender (Oktober 2021–Dezember 2024). Die Längsschnittstudie setzt sich aus den folgenden drei Erhebungsbereichen zusammen:

(1) Monitoring der Kompetenzaneignung
(2) Vertiefende Untersuchungen spezifischer Herausforderungen digitaler Alltags- und Studienpraktiken
(3) Systematische Einbindung und Analyse der Interventionsmaßnahmen zur digitalen Kompetenzdiagnose und -entwicklung

Zum (1) *Monitoring der Kompetenzaneignung* kommen v.a. quantitative Erhebungsverfahren zum Einsatz, um die Phänomene alltäglicher Aneignungsprozesse digitaler Kompetenzen zu erfassen. Die Eingangserhebungen dienen der Identifikation (relativ) zeitstabiler Merkmale der Studierendenjahrgänge (2021–2024) zu den Kernelementen des Forschungsprojektes, wie digitales Mediennutzungsverhalten und Lern- und Selbstorganisationsstrategien. Weiterhin dienen (2) *vertiefende Untersuchungen spezifischer Herausforderungen* dazu, Kompetenzaneignungs- und Lernprozesse Studierender sowie Alltagspraktiken, Herausforderungen und Chancen im Umgang mit digitalen Medien zu identifizieren, abzubilden, um daran anlehnend adressaten- und situationsgerechte Lernressourcen zur Förderung der digitalen Kompetenzentwicklung zu konzipieren. Vor diesem Hintergrund zielen qualitative Erhebungsverfahren, wie episodische Interviews und ethnografische Zugänge, aber auch eine quantitative Lerntagebuchstudie darauf ab, spezifische Situationen des Studienalltags im Umgang mit digitalen Medien und Tools zu rekonstruieren und die daraus resultierenden Lern- und Aneignungsprozesse Studierender abzubilden, welche die digitalen Kompetenzentwicklungsprozesse leiten. Zur (3) *systematischen Einbindung und Analyse der Interventionsmaßnahmen,* die als Kernprodukte in *AP3-5* entwickelt und erprobt werden, kommen Lern- und Lehrmaterialien, hybride Lernformate sowie barrierefreie OERs zur Vermittlung transformativer digitaler Kompetenzen zum Einsatz. Dies erfolgt u.a. durch begleitende Lehrforschungsprojekte und Seminare in den beteiligten Universitäten.

Das AP2 ***‚Entwicklung des digitalen Basispakets Open Work & Study‘*** (HSU) setzt an der studienbezogenen Infrastruktur für das digitale Studium an und definiert ein Hard- und Softwarepaket mit hoher technischer Funktionalität, das als Grundausstattung für das geistes- und sozialwissenschaftliche Studium dient. Die Studierenden der drei Fachbereiche (Fakultät GeiSo) werden durch die Etablierung von Service-Strukturen von sämtlichen administrativen Aufgaben entlastet.

Im AP3 ***‚Entwicklung eines Tools zur Diagnose und Weiterentwicklung digitaler Kompetenzen‘*** (WeTeK Berlin & InfAI Leipzig) wird basierend auf dem EU-Referenzrahmen (DigComp) das ComDigi-S* als eine adressatengerechte und alltagsnahe offene Lernressource (OER) entwickelt, um für die Studierenden lernförderliche Gelegenheitsstrukturen zu schaffen, die der Aneignung digitaler Kompetenzen dienen. Der Wissensstand der Studierenden wird zunächst erfasst (ComDigiS* Test) und in individualisierbaren Lernpfaden (ComDigiS* Train) erweitert.

Das AP4 ***‚Entwicklung und Pilotierung kollaborativer und hybrider Lehr- und Lern-Settings an Hochschulen‘*** (Julius-Maximilians-Universität Würzburg) zielt auf die didaktisch-methodische Entwicklung und Pilotierung hybrider Lehr-Lern-Settings für eine zeitgleiche Online- und Präsenzteilnahme zur hochschulübergreifenden und internationalen Zusammenarbeit im digitalen Raum ab. Schwerpunkte sind die partizipative Förderung digitaler Schlüsselkompetenzen der Studierenden für und in hybriden Lehr-Lern-Settings, die Entwicklung offener Lernressourcen (OER) zum Einsatz in diesen Settings und die technische Ausstattung eines Pilot-Seminarraums.

Das AP5 ***‚Diversität und Partizipation im digitalen Lernen‘*** (Universität Duisburg-Essen) knüpft an der zu nutzenden Ressource der Diversität Studierender an, um lernförderliche Gelegenheitsstrukturen zur Aneignung transformativer digitaler Kompetenzen zu schaffen. Unter dem Aspekt der Barrierefreiheit werden Diversitätsressourcen und Gelingensbedingungen für studentische Partizipation in und für die Professionalisierung in digitalen Lernsettings erforscht und gefördert.

Alle im Projekt entwickelten OER-Produkte stehen im Anschluss auch anderen Hochschulen sowie weiteren Bildungssegmenten der Aus- und Weiterbildung innerhalb und außerhalb der Bundeswehr zur Verfügung.

V. Vorstudie: multiperspektivische Analysen zu Bedarfslagen und Anforderungen des digitalen Studierens (AP1)

Im Rahmen der bereits abgeschlossenen Bedarfs- und Anforderungsanalyse mit Studierenden der Fakultät GeiSo [23] konnte anhand multimethodischer Zugänge rekonstruiert werden, dass die Ausgangslage, die Gestaltungsformate der Online-Lehre und der Einsatz digitaler Lern- und Kollaborationsplattformen aufgrund der veränderten Studiensituation während der pandemischen Gesamtlage (Erhebungszeitraum: Frühjahr 2020 – Winter 2021) in den Fakultäten unterschiedlich war. So nehmen z.B. Live-Sitzungen *mit* Aufzeichnungen in den sog. technikaffinen Fakultäten (MB/ET) einen deutlich größeren Stellenwert ein (41,9% vs. 13,5%), als in den nicht-technikaffinen Fakultäten (GeiSo/WiSo), in denen Live-Sitzungen *ohne* Aufzeichnungen dominieren (77,3% vs. 47,3%; ibid., S.21f.). Über den Zeitverlauf eines Jahres nehmen Live-Sitzungen insgesamt stetig zu (ibid., S.18), wohingegen asynchrone Arbeitsaufträge leicht abnehmen, aber zugleich variantenreicher werden (durch den Einsatz z.B. von OERs, digitale Kollaborationsplattformen).

Ergebnisse aus einer Masterarbeit [24] und den Vorstudien zur Bedarfslage und Anforderungen des digitalen Studiums [23] zeigen zudem, wie divergent Lehrende und die militärischen Vorgesetzten an der HSU die vorhandenen digitalen Fähigkeiten der Studierenden (zwischen wissenschaftlicher Recherche, digitaler Kollaboration, datenethischem Basiswissen und online-gestütztem Selbststudium) einschätzen (ibid.). Zugleich wird sichtbar, wie „heterogen“ die Ausstattung mit digitaler Technik, die Softwarenutzung und die digitalen Fähigkeiten der Studierenden gelagert sind. Dies deckt sich mit Befunden anderer Studien zur digitalen Ungleichheit in Hochschulen [8]. Es lohnt sich also eine vertiefende Analyse der konkreten Nutzungsstrukturen digitaler Technologien und der digitalen Alltagspraktiken in Studium und Freizeit, wie sie bei DigiTaKS* für die noch folgenden Forschungsphasen angelegt ist (s.o.). Weiter auszudifferenzieren sind dann auch erste Einschätzungen, wonach die individuellen Aneignungsprozesse digitaler Kompetenzen häufig aus inzidentellen Lernprozessen resultieren, Studierende zugleich aber verschiedentliche Aspekte benennen, die aus ihrer Sicht „für eine strukturierte Vermittlung digitaler Kompetenzen im Rahmen des Studiums sprechen“ [24, S.54]. Es geht um die Durchdringung des Wechselgeschehens zwischen nicht intentionalen Lernanlässen (wenn im (Studien-)Alltag z.B. Differenzerfahrungen auftreten im Umgang mit dem Digitalen nun nicht mehr als Freizeitinstrument, sondern als Lernraum) und informellen bis formalen digitalen Lernarrangements (Nutzung von Lernplattformen wie ILIAS, moodle etc.; hybride Lernsettings; Einsatz von Online-Tutorials, OERs u.v.m.). Ziel ist sowohl die Förderung der Sensibilität für das Digitale als Lernraum, für Problemlösekompetenz als auch der Möglichkeit einer selbstständigen und proaktiven Auseinandersetzung mit digitalen Technologien.

VI. Nutzungs- und Wirkungsstudie (AP1): Erste Ergebnisse

Im Folgenden werden erste Befunde der Fragebogenerhebung im Rahmen der Eingangserhebung des Studierendenjahrgangs (Jg21) vorgestellt, welche innerhalb der Nutzungs- und Wirkungsstudie (s.o. Monitoring der Kompetenzaneignung) erfolgte. Diese zielt zum einem darauf ab, Einblicke in die digitalen studien- und freizeitbezogenen Lern- und Nutzungsweisen der Studierenden zu gewinnen sowie Tendenzen in den digitalen Kompetenzen abzubilden. Zum anderen stehen eine daran anknüpfende adressatengerechte und lernförderliche Gestaltung der Diagnose- und Entwicklungstools im Fokus dieser Studie. Insgesamt 204 Studienanfänger:innen der Geistes- und Sozialwissenschaften erhielten hierzu im ersten Quartal 2022 Einladungen zur Teilnahme an der Eingangserhebung. Bezogen auf den gesamten Studierendenjahrgang lag die Rücklaufquote nach Abschluss des Erhebungszeitraumes (27.01.2022–30.03.2022) bei 49 %. Nach der Datenaufbereitung konnten 95 gültige Datensätze in die Analyse einbezogen werden.

A. *Charakteristika der Studierendengruppe*

Der Großteil der befragten Studierenden der Fakultät GeiSo ist männlich (66 %) und im Mittel 23,5 Jahre alt. Berufsausbildungserfahrungen weisen 12 % der Studierenden auf und ein Drittel der Studierenden besitzt bereits Studienerfahrungen (30 % Aufnahme vorheriges Studium; i.d.R. ohne Studienabschluss). Dies lässt darauf schließen, dass ein nicht unerheblicher Anteil von Studierenden bereits erste Erfahrungen mit digitalen Hochschultechnologien oder digitalen Lern- und Nutzungsweisen im Studium besitzt. Diese werden im Folgenden spezifiziert:

B. *Digitales Lern- und Nutzungsverhalten (Studium und Freizeit)*

Digitale Medien bieten Studierenden eine große Bandbreite an Nutzungsweisen, die der Gestaltung des Studienalltags wie der Freizeit dienen. Breitschwerdt, Thees und Egetenmeyer [25] differenzieren digitale Medien begrifflich weiter aus, indem sie als *digitale Medienarten* die Gesamtmedien, auch hinsichtlich der Hardware unterscheiden (z.B. Fernseher / Computer) von *digitalen Werkzeugen* (z.B. Textverarbeitungssoftware) und hiervon drittens die mediale Aufbereitung und Vermittlung von Inhalten in Form *didaktisch-strukturierter Medienangebote* abgrenzen. Diese Klassifikation bildet den Referenzrahmen für die deskriptive Analyse in *DigiTaKS**, wobei grundsätzlich zwischen einem *studien- und freizeitbezogenen Nutzungsverhalten* ([7]) unterschieden wird.

Die DigiTaKS*-Eingangserhebung im Studierendenjahrgang 2021 weist auf entsprechende Unterschiede in der Nutzung *digitaler Medienarten* hin: Werden für studienbezogene Anlässe vor allem Laptops, Smartphones und ein zweiter Bildschirm verwendet, so greifen Studierende in der Freizeit bevorzugt auf Smartphones, Laptops, TV-Geräte und Wearables (z.B. Smartwatches) zurück. Folglich werden im Kontext des *Studiums* insbesondere sogenannte „Gesamtmedien“ [25] verwendet, die spezifische Arbeitsweisen bedienen können. In der *Freizeit* kommen hingegen erwartungsgemäß bevorzugt Gesamtmedien zum Einsatz, die auf Unterhaltung, Konsum und den sozialen Austausch ausgerichtet sind. Da sich hier spätestens durch Online- oder hybride Lernsettings zunehmend Schnittmengen ergeben, ist nicht mehr die Technik ausschlaggebend, sondern vielmehr die konkrete Nutzung: Hinsichtlich dieser zeichnet sich ab, dass Studierende in der Freizeit weitaus häufiger auf *digitale Werkzeuge* zurückgreifen als im Studium. Dies entspricht auch den empirischen Widerlegungen zum Mythos der *digital natives* als per se digitalkompetente Lernende (zuletzt: [8]). Deshalb ist Ziel bei *DigiTaKS** das Nutzungsverhalten, Erfahrungen und Einschätzungen spezifischer herauszuarbeiten:

So kennzeichnen die freizeitbezogenen Nutzungsweisen ein präferierter Rückgriff auf Messenger-Dienste und soziale Netzwerke, wohingegen in studienbezogenen Kontexten neben Messenger-Diensten auch Office-Programme und Cloud-Speicherdienste verwendet werden. Inwieweit dies individuell-reflexiv, studienbezogen-situativ oder initial-initiiert durch Lehrende, Peers o.a. erfolgt, können wir an dieser Stelle noch nicht beantworten. Bezogen auf das *Lernen unter Verwendung didaktisch-strukturierter Medienangebote* zeigen sich zumindest Präferenzen (s. Abbildung 1): die Studierenden nutzen digitale Texte (z.B. E-Books, PDF-Dokumente) und Präsentationen/Übersichten. Seltener kommen Online-Lernvideos und Wissensblogs zum Einsatz und so gut wie nie werden Online-Kurse genutzt:

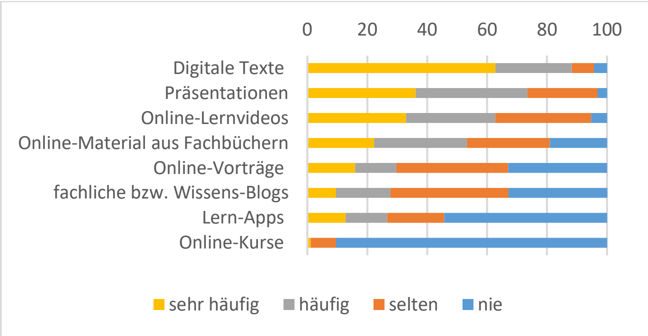


Abbildung 1: Nutzung didaktisch-strukturierter Medienangebote (n=95).

An dieser Stelle bleibt unklar, welche konkreten zentral oder dezentral zur Verfügung gestellten Lehr- und Lernmaterialien durch die Studierenden noch weiterhin verwendet werden. Es ist anzunehmen, dass für Lernaktivitäten differenziert Lehr- und Lernmaterialien – anlassbezogen – ausgewählt werden. Darüber hinaus ist davon auszugehen, dass digitale Strategien genutzt werden, die alltagskulturell vertraut sind und eine (routinierte) Anwendung finden [8]. An dieser Stelle bleibt jedoch unklar, welche konkreten Lehr- und Lernmaterialien durch die Studierenden wie (analog, digital) verwendet werden, welche situationsspezifischen Unterschiede sich hiervon ableiten lassen und inwiefern diese Materialien zuvor Qualitäts- und Selektionsprozesse (z. B. durch die Auswahl der Textmaterialien durch die Dozierenden) durchlaufen haben. Differenzierte Hinweise auf *Präferenzen im digitalen Lernverhalten* konnten anhand strukturentdeckender Analyseverfahren abgebildet werden. Auf der Grundlage der explorativen Faktorenanalyse ließen sich unter Berücksichtigung der lernbezogenen Nutzung verschiedener didaktisch-strukturierter Medienangebote folgende *drei Faktoren der Präferierung* herausarbeiten: (1) Wissenschaftliche Tiefe (2) Komprimierte Darstellung (3) Strukturierte Darstellung (Tabelle I).

TABELLE I: *PRÄFERENZFAKTOREN IN DER NUTZUNG DIGITALER MEDIEN ZUM LERNEN*

	Wissen-schaftliche Tiefe (1)	**Kompri-mierte Dar-stellung (2)**	**Struktu-rierte Dar-stellung (3)**
Digitale Texte (z.B. E-Books, PDF-Dokumente)	0.663		
fachliche bzw. Wissens-Blogs	0.773		
zusätzliches Online-Material aus Fachbüchern	0.754		
Präsentationen/Übersichten		0.668	
Online-Lernvideos		0.820	
Online-Vorträge (z.B. TED Talks)		0.789	
Lern-Apps (z.B. Duolingo, Babbel)			0.774
Online-Kurse (z.B. MOOCs, iMooX)			0.756
Anmerkung: Hauptkomponentenanalyse; Rotation Varimax			

Digitale Medien, die *tiefergehende wissenschaftliche Auseinandersetzungen mit spezifischen Themengebieten (1)* ermöglichen, kennzeichnen sich durch eine Vielfalt an Lehr- und Lernmaterialien, welche überwiegend in Form digitaler Texte, fachlicher Blogs und zusätzlicher Online-Materialien zur Verfügung stehen. Diese gewährleisten ein tiefergehendes Verständnis ausgewählter Inhaltsbereiche, bei einem gleichwohl hohen zeitlichen Aufwand für die Sichtung entsprechender Materialien. Dies relativiert den Mythos um zeitliche Flexibilität im digitalen Raum; auch digital zur Verfügung stehende Materialien erfordern in einer tiefergehenden Auseinandersetzung (Lern)Zeit.

Digitale Medien, die eine *komprimierte Darstellung der Lerninhalte (2)* bieten, ermöglichen eine ortsflexible wie beschleunigte Erarbeitung von Themenbereichen, da zumeist ein schneller audiovisueller Überblick gegeben wird. Zu diesem Faktor lassen sich die folgenden digitalen Medien zuordnen: Präsentationen/Übersichten, kurze Online-Lernvideos und komprimierte Online-Vorträge wie z.B. TEDs.

Digitale Medien, die sich unter den Bereich der *strukturierten Darstellung (3)* subsumieren lassen, umfassen vorstrukturierte Lehr- und Lernmaterialien, die bereits umfangreiche Qualitätsprüfungen durchlaufen haben und für die ein Abonnement notwendig ist. Damit ist der Zugang zwar kein ‚easy-in' mehr, aber die i.d.R. geprüfte und didaktisierte Struktur bietet einen pädagogisierten Lernraum.

Die kommenden Forschungsphasen in *DigiTaKS** werden durch empirisch veränderte Methodik (Interviews; ethnographische Beobachtungen; Tagebuchstudie) weitergehend auch situationsbezogene und individuelle Unterschiede in den Nutzungsweisen herausarbeiten können.

C. Selbsteinschätzung digitaler Kompetenzen

Neben der Identifikation des digitalen Lern- und Nutzungsverhaltens dient der Eingangsfragebogen dazu, vertiefende Einblicke in die Selbsteinschätzung digitaler Kompetenzen Studierender zu erhalten. Dazu wurden die Studierenden gebeten, die eigenen digitalen Kompetenzen auf einer fünfstufigen Likertskala (1=*stimme überhaupt nicht zu* bis 5=*ich stimme voll und ganz zu*) einzuschätzen (s. TABELLE II):

TABELLE II: *SELBSTEINSCHÄTZUNG DIGITALER KOMPETENZEN*

	Selbsteinschätzung digitaler Kompetenzen				
	N	***min***	***max***	***MW***	***Std.***
Kommunizieren und Kollaborieren	94	2.00	5.00	4.5	.57
Unterrichten und Implementieren	93	1.00	5.00	4.2	.84
Suchen und Verarbeiten	93	2.00	5.00	4.1	.69
Schützen und sicher Agieren	94	1.67	5.00	4.1	.80
Analysieren und Reflektieren	93	2.00	5.00	4.0	.75
Produzieren und Präsentieren	94	1.67	5.00	4.0	.85
Problemlösen und Handeln	93	2.20	5.00	3.8	.72
Anmerkung: Mittelwertsangaben auf der Grundlage einer fünfstufigen Likertskala von 1= *ich stimme überhaupt nicht zu* bis 5= *stimme voll und ganz zu*					

Die Mittelwertvergleiche der Kompetenzbereiche deuten auf eine moderate bis hohe Selbsteinschätzung der Kommunikations- und Interaktionsfähigkeit im Umgang mit digitalen Medien hin. Als weiterhin hoch beurteilen die Studierenden auch die Fähigkeiten beim Unterrichten und Implementieren von digitalen Lerninhalten (wenn sie also z.B. in Form von Referaten Lerninhalte für andere aufbereiten). Niedrigere Werte zeigen sich für das Problemlösen im Umgang mit digitalen Werkzeugen und Tools (TABELLE II).

Die Ergebnisse lassen den Schluss zu, dass im eigenen Selbstbild vor allem Defizite im Lösen konkreter Probleme im Studienalltag mittels digitaler Technologien wahrgenommen werden. Wie diese als lernauslösendes Krisenmoment charakterisiert bzw. transformationstheoretisch als „desorientierende Dilemma" lernhaltig werden und wie die Studierenden mit ebendiesen umgehen, wird in vertiefenden Untersuchungen im Rahmen der längsschnittlichen *DigiTaKS**-Begleitung der Studierenden fokussiert folgen. Vor diesem Hintergrund geben Standardabweichungen von Einzelaussagen der Kompetenzbereiche (s. TABELLE II) bereits Hinweise auf Bedarfe Studierender hinsichtlich einer vertiefenden Diagnose und dann auch der Förderung digitaler Kompetenzen.

D. Nutzung von Tools zur Selbstorganisation

Die pandemischen Entwicklungen haben maßgeblich dazu beigetragen, dass die Anforderungen an die Selbstorganisationsfähigkeiten der Studierenden zugenommen haben. So deuten die Ergebnisse der initialen Bedarfs- und Anforderungsanalyse darauf hin, dass die zeitliche Organisation des (digitalen) Studienalltags eine entscheidende Herausforderung für Studierende darstellt. Die digitalisierte Hochschullehre weiß darum und längst ergänzen entsprechende digitale Medienangebote bestehende digitale Werkzeuge, um studienbezogene Aufgaben, Fristen und Termine zu organisieren [7], [23]. Dies steigert die individuelle Selbstorganisation durch neu hinzukommende digitale Tools; zugleich wird die bisherige Selbstorganisation so kollektiv (vor)strukturiert und teilweise auch standardisiert (Rundmails; Bulletins; pop-up-reminder u.a.).

Auf Grundlage der Ergebnisse der Eingangsbefragung lässt sich skizzieren, dass bevorzugt digitale Kalender, handschriftliche Notizen (analoge Post-it; To-Do-Listen) und digitale Notizen von den Studierenden zur Selbst- und Studienorganisation genutzt werden. Hingegen nutzen die Studierenden, digitale To-Do-Software, digitale Assistenten und analoge Kalender deutlich weniger. Allerdings verweisen die hohen Standardabweichungen der einzelnen Werte auf eine hohe Heterogenität in der Nutzung entsprechender Tools, deren Hintergründe im Zusammenhang sowohl entlang der bekannten digital divide levels als habituell divergente „Digitalisierungsgrade“ [8] weiter zu untersuchen sind. Darüber hinaus möchte *DigiTaKS** auch situationsabhängige Spezifika der Selbst- und Studienorganisation abbilden, wozu es gesonderter, insbesondere qualitativer Erhebungsverfahren bedarf.

VII. Schlussfolgerung für weitere Forschungsschritte

Die aus der *Faktorenanalyse zum Nutzungsverhalten digitaler Medien zum Lernen* gezogene Systematisierung verweist auf eine individuell unterschiedliche, wie zugleich anlassbezogene Auswahl bestimmter Medienangebote durch die Studierenden. Welche Rolle hier digitale Alltagsroutinen oder erst im Studienalltag entwickelte Präferenzen für die Entwicklung transformativer digitaler Kompetenzen spielen, wird aktuell für weitere Studienjahrgänge (Jg22; Jg23) erforscht und in tiefergehenden Rekonstruktionen und Interventionen erweitert. Ob sich diese Mediennutzung z.B. mit unterschiedlichen Lern- und Nutzungstypen verbinden lässt, wird Teil von begleitenden Beobachtungen im Studienalltag sein. Ebenso ist geplant, über wiederholte Erhebungswellen im Laufe des Studiums der drei verschiedenen Jahrgänge einen Längsschnittvergleich zur Selbsteinschätzung digitaler Kompetenzen zu erzielen, der Varianzen im zeitlichen Verlauf widerspiegelt und Erkenntnisse über die Kompetenzentwicklung im Studienverlauf erbringt. Einen besonderen Stellenwert nimmt hierbei die Ausgestaltung des Hard- und Softwarepakets (AP2) und der offenen Lernressource ComDigi-S* (AP3) ein. Darüber hinaus soll den projektintern entwickelten kollaborativen und hybriden (AP4) sowie barrierefreien Lehr- und Lernsettings (AP5) eine besondere Bedeutung für eine zeitgemäße Gestaltung hochschulinterner Gelegenheitsstrukturen zur Förderung transformativer digitaler Kompetenzniveaus Studierender zukommen.

Danksagung

Die Autor:innen bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [DigiTaKS*].

Literatur

[1] F. Stalder, *Kultur der Digitalität*, Erste Auflage, Originalausgabe. Berlin: Suhrkamp, 2016.

[2] A. Nassehi, *Muster: Theorie der digitalen Gesellschaft*. München: C.H. Beck, 2019.

[3] Zukunftsinstitut, „Konnektivität. Was kommt nach der Digitalisierung?“ 2022.

[4] J. Noller, „Ontologie der Digitalität. Zur virtuellen Realität der Neuen Medien“, in *Digitalisierung als Transformation? Perspektiven aus Ethik, Philosophie und Theologie*, T. Holischka, K. Viertbauer, und C. Preidel, Hrsg. Berlin, Heidelberg: Springer, 2022, S. 3–17. doi: 10.1007/978-3-662-65350-0_1.

[5] OECD, *Future of Education and Skills 2030 Concept Note*. 2019. Zugegriffen: 22. August 2022. [Online]. Verfügbar unter: https://www.oecd.org/education/2030-project/teaching-and-learning/learning/skills/Skills_for_2030_concept_note.pdf

[6] J. Ebeling, H. Koch, und A. Roth-Grigori, Hrsg., *Kompetenzen im kritischen Umgang mit Daten. Data Literacy Education an deutschen Hochschulen*. 2021. [Online]. Verfügbar unter: https://www.stifterverband.org/medien/kompetenzerwerb-im-kritischen-umgang-mit-daten

[7] G. Janschitz *u. a.*, *Alle(s) digital im Studium?!: Projektbericht der Steirischen Hochschulkonferenz zur Analyse digitaler Kompetenzen von Studienanfänger*inne*n*. Graz: Graz University Library Publishing, 2021. doi: 10.25364/978-3-903374-00-3.

[8] G. Janschitz, „Digitale Ungleichheiten im Hochschulbereich“, in *Organisationen in Zeiten der Digitalisierung*, C. Onnen, R. Stein-Redent, B. Blättel-Mink, T. Noack, M. Opielka, und K. Späte, Hrsg. Wiesbaden: SpringerVS, 2022, S. 101–126. doi: 10.1007/978-3-658-36514-1_6.

[9] U.-D. Ehlers und S. A. Meertens, *Studium der Zukunft – Absolventen der Zukunft: Future Skills zwischen Theorie und Praxis*. Springer VS, 2020.

[10] S. Schreiber-Barsch, H. Gundlach, und K. M. Pongratz, „Hochschulen als inklusive Lernorte“, in *Von der Exklusion zur Inklusion. Weiterbildung im Sozialsystem Hochschule*, DGWF, Hrsg. Bielefeld: W. Bertelsmann, 2020, S. 117–133.

[11] M. Kerres, „Bildung in der digitalen Welt: Über Wirkungsannahmen und die soziale Konstruktion des Digitalen“, *MedienPädagogik: Zeitschrift für Theorie und Praxis der Medienbildung*, Bd. 17, S. 1–32, 2020, doi: 10.21240/mpaed/jb17/2020.04.24.X.

[12] D. Yacek, „Die transformative Wende in der Erziehungswissenschaft. Eine Einleitung in den Themenkomplex ‚Bildung und Transformation‘“, in *Bildung und Transformation: Zur Diskussion eines erziehungswissenschaftlichen Leitbegriffs*, D. Yacek, Hrsg. Berlin, Heidelberg: J.B. Metzler, 2022, S. 1–8. doi: 10.1007/978-3-662-64829-2_1.

[13] E. W. Taylor, „Transformative learning theory“, in *Transformative Learning Meets Bildung: An International Exchange*, A. Laros, T. Fuhr, und E. W. Taylor, Hrsg. Rotterdam: Sense Publishers, 2017, S. 17–29. Zugegriffen: 12. September 2019. [Online]. Verfügbar unter: https://www.springer.com/de/book/9789463007979

[14] H.-C. Koller, *Bildung anders denken: Einführung in die Theorie transformatorischer Bildungsprozesse*. Stuttgart: Kohlhammer, 2012.

[15] A. Laros, T. Fuhr, und E. W. Taylor, Hrsg., *Transformative Learning Meets Bildung: An International Exchange*. Sense Publishers, 2017. Zugegriffen: 12. September 2019. [Online]. Verfügbar unter: https://www.springer.com/de/book/9789463007979

[16] S. Schmidt-Lauff, „Bildung“, in *Zeit im Lebensverlauf: Ein Glossar.*, S. Schinkel, S.-M. Köhler, F. Hösel, A. König, E. Schilling, J. Schreiber, R. Soremski, und M. Zschach, Hrsg. Bielefeld: transcript, 2020, S. 67–72.

[17] J. Mezirow, *Transformative learning theory*. Routledge, 2018, S. 114–128. doi: 10.4324/9781315147277-8.

[18] Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, Hrsg., *Unsere gemeinsame digitale Zukunft*, Redaktionsschluss: 12.04.2019. Berlin: Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU), 2019.

[19] A. Martin, „Digital Literacy and the “Digital Society”“, in *Digital Literacies: Concepts, Policies and Practices*, C. Lankshear und M. Knobel, Hrsg. New York: Peter Lang, 2008, S. 151–176.

[20] S. Carretero, R. Vuorikari, und Y. Punie, *DigComp 2.1. The digital competence framework for citizens. With eight proficiency levels and examples of use.* Luxembourg: Publications Office of the European Union, 2017. Zugegriffen: 27. April 2021. [Online]. Verfügbar unter: https://data.europa.eu/doi/10.2760/38842

[21] R. Vuorikari, S. Kluzer, und Y. Punie, *DigComp 2.2, The Digital Competence framework for citizens: with new examples of knowledge, skills and attitudes*. Luxembourg: Publications Office of the European Union, 2022. Zugegriffen: 30. Juni 2022. [Online]. Verfügbar unter: https://data.europa.eu/doi/10.2760/115376

[22] F. Rauner, L. Heinemann, A. Maurer, und B. Haasler, *Competence Development and Assessment in TVET (COMET): Theoretical Framework and Empirical Results*. Singapore: Springer, 2013.

[23] M. Rathmann, T. Rosemann, J. Schiller, J. Schwarz, und S. Schmidt-Lauff, „Digitalität als Herausforderung und Chance. Eine multiperspektivische Analyse zu Bedarfslagen und Anforderungen des digitalen Studierens: Abschlussbericht zur Bedarfs- und Anforderungsanalyse (05/2021 – 10/2021) im Rahmen des Projekts ‚DigiTaKS* – Digitale Schlüsselkompetenzen für Studium und Beruf‘“, Helmut-Schmidt-Universität Hamburg, Juli 2022. doi: 10.24405/14354.

[24] E. A. Steinmetz, „Digitale Kompetenzen im Studium“, Thesis, Helmut-Schmidt-Universität/Universität der Bundeswehr, 2021. doi: 10.24405/13973.

[25] L. Breitschwerdt, A. Thees, und R. Egetenmeyer, „Digitale Medien in der Erwachsenenbildung/Weiterbildung“, *Magazin erwachsenenbildung.at. Das Fachmedium für Forschung, Praxis und Diskurs*, Bd. 44–45, S. 11-1-11–12, 2022.

Working from home: Opportunities and risks for working conditions, leadership, and health

Jörg Felfe[1]*, Annika Krick[1], Sven Hauff[1], Karl-Heinz Renner[2], Laura Klebe[1], Katharina Schübbe[1], Dorothee Tautz[1], Yannick Frontzkowski[1], Philip Gubernator[1], Stephanie M. Neidlinger[1]
[1] *Helmut Schmidt University,* Hamburg, Germany
[2] *Universität der Bundeswehr,* Munich, Germany
*felfe@hsu-hh.de

Abstract – **The current COVID-19 pandemic has led to a rapid increase in digital and virtual work, as well as new leadership challenges (remote work, working from home, web conferences, digital leadership etc.). It can be expected that these "new ways of working" will continue their influence on our working lives. This study is part of a larger research program "Digital Leadership and Health" which 1) investigates consequences of working from home (i.e., home-office) on commitment, engagement, and employee health, and 2) aims at identifying facilitating and obstructing design options for an effective and sustainable use of digital ways of working and takes leadership and health promotion into consideration. On this basis, 3) recommendations for an effective and sustainable use of digital working and leading will be derived (technical guidance, rules of conduct for leaders and employees, HR strategies). As a practical tool, a survey and feedback platform for leadership assistance will be developed. With this tool companies can easily evaluate their quality of digital work and leadership. In this paper the focus is on examining consequences of working from home on the basis of a survey with *N* = 3652 employees and leaders in Germany.**

Keyword – Leadership, working from home, remote work, home-office, job satisfaction, commitment, health

I. Introduction

The Covid-19 crisis caused tremendous changes in the working context. To avoid getting infected and spreading the virus many employees had to work from home. For many employees, the work that used to be done in the office now takes place at home, i.e., in the home-office. Accordingly, working from home (WfH) increased significantly in most organizations [1]. WfH is supposed to bring both challenges and opportunities. Positive consequences are for example better opportunities to integrate family and work, less interruptions from colleagues and less commuting [2]. Negative consequences are reduced communication with colleagues, isolation and an inadequate home-office environment (e.g., no separate room for work activities, poor internet connection …) [3].

Leaders experience a particularly strong transformation and challenges in their daily working life [4]. Previous literature has already suggested that leadership concepts from the traditional office setting cannot be simply transferred to the remote setting [5]. For example, leaders report an increase in working hours, additional administration and difficulties in keeping in touch with their followers [4]. Moreover, reduced contact and digital communication emerge as difficulties in motivating followers and in maintaining trust in their work ethics and engagement [6, 7].

While there is a first understanding of general challenges and demands for working and leading in the traditional office setting, the impact of WfH for leaders and employees is still unclear. For future work design and leadership, it is important to better understand the demands and resources that come along with WfH and how leaders may cope with challenges in this context.

Against this background, the current research project "Digital Leadership and Health" aims at deepening the understanding of opportunities and risks of working and leading in a digital context. Using a mixed methods approach, we conduct literature reviews, qualitative interview studies, longitudinal surveys, and laboratory experiments. The findings will be used to develop a survey and feedback platform to assist leaders when their teams are working from home. The project is part of the "Digitalization and Technology Research Center" of the Bundeswehr (dtec.bw).

The study and findings presented in this paper contribute to a better understanding of WfH by addressing three research questions on a quantitative empirical basis: a) what are consequences of WfH for working conditions in terms of resources and demands, b) what are the consequences of WfH for job satisfaction, engagement and health, and c) how can leadership be successful in the context of WfH (digital leadership)? To answer these questions, we conducted a comprehensive Germany wide, cross-industry survey, in which employees and leaders were asked about the differences between the traditional office setting and working from home, using a standardized set of instruments.

II. Working from home

Previous studies already suggest specific differences between the traditional office and WfH. For example, employees working from home experience greater flexibility, especially with regard to working hours, and also greater freedom of action [8–10]. These resources have a positive effect on employees' own job satisfaction, motivation, and performance and reduce their experience of stress [11, 12]. Working more smoothly with fewer interruptions can be more successful and can thus be an important resource [2, 13]. However, this depends on the circumstances at home. If the workplace has to be shared with the partner or children and/or relatives in need of care have to be looked after from home, this can quickly lead to more distractions and more frequent interruptions and a considerable double burden [14].

https://doi.org/10.24405/14574

Traditional work environments provide a temporal and spatial framework that pre-structures and organizes employees' daily routines (e.g., fixed work and lunch breaks, spatial separation from private life). At home employees must manage without this structure [15]. It is not uncommon for breaks to be eliminated or shorter at home than in the office [16]. In order to compensate for this, a high level of self-management and organizational skills and a good sense of self-awareness are required [17].

Another major benefit of WfH can be seen as the saving of commuting time [2, 18]. However, it unfortunately often happens that the saved time is used for extra work instead of spending it for recreation [8]. Intensification of work and longer working hours is often observed [8, 10, 13, 16].

Workplace equipment is often an issue at home [16, 19]. Appropriate work furniture is often lacking (e.g., working from the sofa; working on the kitchen chair). Technical equipment is also often a problem (e.g., working with a laptop without an external keyboard and large screen). Whereas ergonomic chairs, large monitors, height-adjustable desks, and sufficient internet are usually provided in the office, employees are left to their own devices at home.

Traditional collaboration is also different when working from home. Communication mostly takes place via digital media, such as telephone, e-mails or web conferences. Digital collaboration can lead to more coordination problems [20]. Overall, it seems to be more difficult to receive new information and exchange information spontaneously [20]. Communication via digital media decreases the overall frequency of communication and interaction. Relationship building and informal communication are also perceived as reduced and more difficult [18]. Misunderstandings can also arise more easily, and conflicts can escalate more quickly or, in some cases, be discovered later [21].

On the one hand, web conferencing and digital communication facilitate communication and reduce the feeling of isolation. On the other hand, they can be a burden, especially if web conferencing is frequent, long, and without breaks [22] or if messages and calls lead to frequent interruptions. Since the Corona pandemic, daily web conferencing has increased dramatically [23]. Many workers complain of zoom fatigue due to frequent web conferencing and feel mentally and physically exhausted by web conferencing [22, 24].

As previous studies have shown, social interactions have an overall positive effect on stress experience and well-being [9, 12, 25]. At home, employees spend most of their time alone at their desk. This can lead to feeling isolated and hardly noticing what is going on with the other team members. The lack of social support from colleagues and the leader can pose a risk [13, 26] because social support from colleagues as well as from the leader is an essential resource. This may be limited due to limited contact and lack of physical proximity. Distance may also reduce mutual understanding and trust. It often happens that leaders assume a lower level of commitment and engagement when their team members work from home [27].

At home, the ability to reconcile family and personal obligations with work obligations is better, so that less conflict is experienced between personal and work life [18]. However, it also happens that more conflicts between private and professional life are perceived, especially if there are no separate and quiet rooms at home, and children or family members in need of care have to be looked after. Many employees experience a blurring of boundaries between private life and work [13, 28]. On the one hand, WfH can be an opportunity for better work-life balance, but at the same time it can also lead to a risk of increasing conflicts between work and private life.

While there are numerous references in the literature to different opportunities and risks of WfH, little is known about the frequency and relationships of the respective aspects. This research gap is to be closed with a comprehensive Germany wide, cross-industry survey, in which employees and leaders were asked about the differences between the two settings using a standardized set of instruments.

III. Method

A. Sample and procedere

The study sample consisted of $N = 3.652$ German employees, including $N = 1.353$ leaders (37.7%) from a wide range of industries (metal and electrical industry, chemical and pharmaceutical industry, energy, construction, crafts, logistics, transport and traffic, tourism, hotels and restaurants, banking and insurance, real estate, corporate, legal, personnel and tax consulting, advertising, trade, security, IT and telecommunications, education, training and science, care, medicine and health as well as media, art and culture, and public administration). Participants were surveyed nationwide about their experiences when working from home in four waves (April 2021 - September 2022). Participants with different home-office intensities were included: from no day home-office (HO) (16.2%), 1 or 2 days (24.5%), 3 or 4 days (28.5%) to 5 days HO per week (31 %). 50.03% were male. A prerequisite for inclusion was that the participant's own work can basically be done in the HO.

B. Measures and Analysis

Established scales were used to measure working conditions [29–31], engagement [32]; commitment [33], health [34, 35]. All items were rated on a five-point answer format. Frequencies and correlation analysis were conducted. For easier readability we present "top two boxes".

IV. Results

In the following we present our findings with regard to three research questions: a) what are consequences of WfH for working conditions in terms of resources and demands, b) what are the consequences of WfH for satisfaction, engagement, and health, and c) how succeeds leadership when working from home (digital leadership)?

A. Consequences of WfH for working conditions

How do working conditions differ a) between those who work partly or mainly at home (HO) and those who do not, although this is possible in principle, and b) between the office and home-office work locations for employees who work in both locations?

A.1) Most working conditions are better with WfH - Voluntariness is crucial.

Respondents who work from home rate their overall **autonomy** and **scope of action** at work higher than respondents who only work in the office. For example, 67.5% of HO respondents say their work allows them to take initiative and act on their own discretion. Among employees working only in the office, the percentage is significantly lower at 54.8%. However, the voluntary nature of HO plays a decisive role: the scope for action is perceived as higher (81.3%) when employees work voluntarily at home. Of those respondents who work involuntarily at home, only 48.7% experience a high level of scope for action.

With regard to **workload** (time pressure), there are hardly any differences between employees with and without HO. However, there is a difference in **permanent availability**. Those who work from home report higher requirements with regard to permanent availability outside regular working hours (26%) compared to those who work only in the office (13.9%).

WfH is also associated with frequent **web conferences**, which are often experienced as stressful. 17% of HO respondents report spending most of their day in web conferences, 16% report having no breaks between web conferences, and 23% are still working on other tasks in parallel (multitasking). For respondents working only in the office, the percentages are clearly lower at 4% (frequency), 6% (no breaks), and 12% (parallel work), respectively.

Frequent web conferencing increases the risk of **zoom fatigue**. Of those who spend most of the day in web conferences, 44.7% report that their eyes are strained (e.g., tired, dry, irritated; visual fatigue) and 42.1% that they "prefer to be alone and just have their rest" (social fatigue). In comparison, the percentages of those who never or hardly spend any time in web conferences are about 21% and 20.5%, respectively. Also, closely scheduled web conferencing also increases the risk of zoom fatigue. Of those who almost never have breaks between web conferences, 42.6% report that their eyes are strained (e.g., tired, dry, irritated; visual fatigue) and 46.3% that they "prefer to be alone and just have their rest" (social fatigue). In comparison, the percentages of those with adequate breaks between web conferences are only 19.5% and 19.6%, respectively.

Respondents in the HO who are more exposed to web conferencing experience more stress (r = .27) and discomfort (r = .24) and less job satisfaction (r = -.15). For respondents without HO, associations with stress (r = .23) and discomfort (r = .16) also emerge.

A.2) Direct comparison reveals advantages of WfH - but also risks.

In a direct within comparison, employees who work both in the office and from home assess the working conditions at the two workplaces differently. Their assessments regarding the office workplace hardly differ from the assessments of those who work exclusively in the office which confirms the validity of their assessments. Above all, **flexibility** is rated higher at home (71.0%, e.g., free time management) than in the office (54.2%). Again, the assessment is dependent on voluntariness: employees who voluntarily work from home rate their flexibility at home higher (83.9%) than individuals who perceive a low voluntariness (56.1%). In addition, respondents report fewer **interruptions** from others at home. At home, the percentage of employees who are adversely affected by interruptions is 18.6%. In contrast, when working in the office, the percentage is significantly higher at 37.4%.

Workplace conditions (ergonomics, sufficient space) are also rated worse at home. In the office, the proportion of positive assessments of workplace conditions is 71%, whereas it is only 47.1% at home. However, the assessment of workplace conditions at home is more positive if the respondents work voluntarily at home (53.4%) than if rather involuntarily (39.5%). When working predominantly or exclusively at home, the proportion of positive evaluations of the workplace is higher (53%) than when only working one or two days at home (41.5%). Also, technical problems (e.g., problems with the internet connection) are more frequent at home (e.g., poor internet access 15.6% at home and 11.5% in the office). Accordingly, communication is more complicated and cumbersome at home (20.4%) than in the office (13.1%).

Moreover, employees experience more **isolation** at home. 32.9% of respondents say they feel isolated at home, but only 15.2% when they work in the office. Accordingly, 55.2% report missing direct contact with colleagues at home, whereas only 29.3% in the office. The home-office intensity is also noticeable here. When the HO intensity is high, 54.7% of respondents miss direct contact with colleagues. With a low intensity, it is "only" 48.1%. FIGURE 1 shows direct comparisons of working in the office and from home.

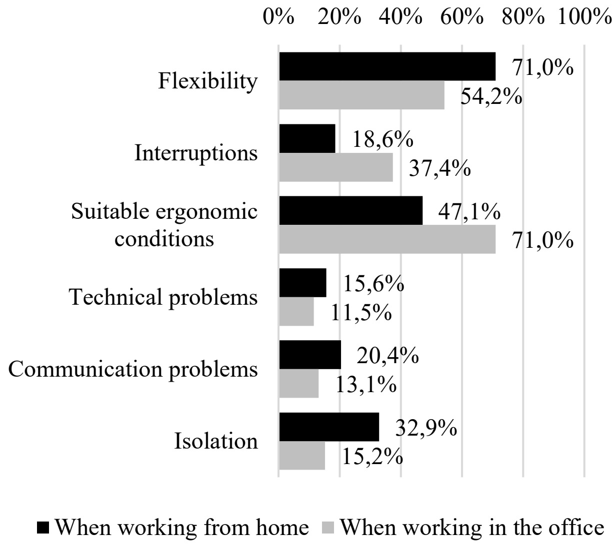


FIGURE 1: DIRECT COMPARISON BETWEEN OFFICE AND HOME-OFFICE.

A.3) Compatibility of family and career.

The **work-life balance** is also rated more positively by respondents who work in HO (69.2%) than without HO (62.7%). Here, the voluntary nature of HO also plays a decisive role: 78.1% perceived compatibility as better when they work voluntarily from home. Among those who work involuntarily at home, only 55.8% experience good compatibility.

It is often the case that employees in the home-office also take on additional care tasks during their working hours ("care work"). Here we distinguish between the care of children and the care of the elderly, people in need of care and people with disabilities. 36.3% of respondents with children who work at home provided intensive childcare. Only 25% of respondents with children have little or no care work at home.

Family environment plays a role in who benefits from working from home. Employees who live with children in a household benefit more from working at home. If employees live with children and can work at least partly from home, 26.1% report a high commitment compared to those who work exclusively in an office (16.7%). Thus, the proportion with high commitment is higher among those with home-office. Vice versa, the proportion of those with low commitment decreases from 48% without HO opportunities to 34.1% when working from home is possible. If employees do not live with children, the place of work makes little difference to their commitment (20.3% have high commitment without HO versus 22.2% with HO). Similar effects are found for well-being showing that employees with children in particular tend to benefit more from WfH in terms of their commitment, engagement, and well-being than employees without children.

Furthermore, it became apparent that childcare was largely performed by women. For this purpose, we looked at children with higher care workloads in the age group up to 14 years. A high care effort in the HO was reported by 57.8% of the women but only 42.5% of the men surveyed. For women, caring for children while working at home also has a more negative impact on performance than for men. Of those with intensive childcare while working from home, 44.4% of men report high work performance, but only 32.6% of women.

B. Consequences of WfH for job satisfaction, engagement, and health

How do satisfaction, engagement, and health differ a) between those who partially or mostly work from home (HO) and those who are only in the office, and b) between employees with different extent of HO?

B.1) Do employees with WfH show higher commitment, satisfaction and engagement?

The ability to work at home is associated with significantly higher levels of **affective organizational commitment**. For example, 52.1% of respondents with HO say they feel a strong sense of belonging to their organization. For employees who only work in the office, the percentage is 43.8%, significantly lower. When it comes to the fit between individual values and the organization, the difference is even more pronounced: 53.7% of HO respondents say that their individual values fit with those of the organization, compared to only 41.2% of office-only respondents. When it comes to sense of belonging, it also comes down to voluntariness: While 61.1% of those respondents who are voluntarily working from home said they felt a sense of belonging to the organization, only 42.5% of those respondents who are involuntarily working from home did. Interestingly, commitment is not highest when working exclusively from home (49.8% with high commitment), but when the HO proportion is in the middle and low range (57.4% with high commitment).

The opportunity to work from home is also associated with somewhat higher **job satisfaction**. For example, 48.9% of respondents with HO report high job satisfaction. For employees who only work in the office, the percentage is slightly lower at 44.4%. Job satisfaction also depends on voluntariness: 58.8% of those respondents who work voluntarily in a home-office say they are satisfied with their work situation. In contrast, only 34.8% of respondents who involuntarily work at the HO are satisfied with their work situation. In contrast to commitment, job satisfaction is highest when the HO intensity is particularly high (52.2% with high satisfaction). When the HO proportion is small, 45.9% report high satisfaction.

The opportunity to work at home is related with a slightly higher level of **engagement**. For example, 37.4% of HO respondents say they are completely "absorbed in their work". Among employees who do not work from home, the percentage is slightly lower at 32.9%. Engagement also comes down to voluntariness, with 45% of respondents who voluntarily work from home reporting a high level of engagement compared to only 28.1% among those who are more involuntarily at home. Interestingly, in contrast to commitment and job satisfaction, engagement is highest when the HO intensity is lower (44.0%) than when fully working at home (37.7%).

B.2) Do leaders and employees rate performance worse in the home-office?

In a direct comparison, leaders assess their employees' **performance** worse in the HO than in the office. In the office, 54% of leaders rate the work performance of their employees as very good to excellent and only 8% as sufficient to satisfactory. In the home-office, only 41% rate the work performance of their employees as very good to excellent but 15% as only sufficient to satisfactory.

A similar but somewhat weaker picture emerges for the employees' self-assessed work performance: their own performance is rated worse in the HO (50% very good to excellent and 15% sufficient to satisfactory) than in the office (53% very good to excellent and 10% sufficient to satisfactory).

B.3) Is WfH beneficial for health?

Employees with the opportunity to work at home report slightly better general **health**. 65.1% of respondents with HO report good general health (scores of 7 and higher on a scale of 0 - 10). Among employees only in the office, the percentage is slightly lower at 60.1%.

Employees who may work from home also report slightly fewer **mental stress** reactions in the past four weeks. Of them, 31.8% report headaches, tension, and back pain, 29.2% feel generally exhausted, and 18.4% feel irritable. Among employees who work only in the office, the proportions of those with mental stress reactions are slightly higher: 35.9% of them report headaches, tension, and back pain, while 33.1% report general exhaustion and 22.4% feel irritable.

B.4) Who benefits more, leaders or followers?

Overall, WfH is associated with higher job satisfaction and commitment, stronger engagement, and improved health. However, leaders and employees benefit slightly different. For example, the positive relationships between WfH and commitment and job satisfaction are more evident among employees (r = .10, .09), but not among leaders (r = .01, .01). Negative correlations even emerge among the group of leaders for health. WfH is even associated with a stronger experience of physical (r = .07) and psychological stress (r = .05) among leaders, whereas the opposite direction occurs for followers (r = -.05, -.05).

C. Risks and opportunities with digital leadership

How do leaders communicate with their employees? What is happening to informal communication? What is the significance of frequent web conferences? How much do leaders trust their employees in the HO? What form does digital leadership take? What difficulties do leaders experience?

C.1) Digital communication with leaders prevails at home.

Most respondents communicate with their leader 1 to 2 times per week (38%), 20% have contact only every few weeks or less frequently, 42% have more frequent exchanges, of which 22% communicate daily. **Daily communication** decreases with increasing HO intensity: if only in the office 36.1% have daily contact but with fulltime HO it is only 14.5%. Communication frequency with the leader has a positive effect on health, satisfaction, and performance: e.g., on engagement (r = .15), commitment (r = .21), health (r = .15).

Overall, 46% of the respondents communicated predominantly or exclusively digitally with their leaders while only 27% had predominantly direct **face-to-face** contact. As expected, the face-to-face communication decreases with increasing HO intensity (r = -.66). Among those who work in the office only, the face-to-face communication is 61.3% and the digital communication part is only 23.4%. In contrast, for those who work primarily from home (4 or 5 days), the face-to-face share is only 5% and the digital share is 85%. Remarkable, the more face-to-face communication, the more **informal communication** takes place (r = -.15).

C.2) Informal communication with leader suffers at home

In a direct comparison, respondents rate informal communication with their leaders in the HO worse than in the office. For example, only 29.3% of respondents state that their leader in the HO "takes time to talk spontaneously about private matters in between" or 28.7% state that the leader shows private interest "... and often asks what is going on". In the office, the proportion is significantly higher at 48.5% and 39.1%, respectively.

Although on a higher level, as is also the case with the other leadership behaviours, the leaders confirm this picture. For example, 49.4% of leaders state that they "take time to talk spontaneously about private matters in between" and 50.6% state that they are "interested in their employees as a private person and often ask what is going on" in the HO. In the office, the percentages are significantly higher: 75.9% and 68.4%, respectively.

Overall, the possibility of developing and maintaining informal contacts between employees and leaders is significantly more limited in the HO than in the office, both from the perspective of the employees and the leaders. From the followers' perspective, more informal communication in the HO is related to less stress (r = -.16), more well-being (r = .22), commitment (r = .34), engagement (r = .35), job satisfaction (r = .32), and performance (r = .17).

C.3) More face-to-face communication after pandemic

Leaders and followers alike assume that their communication behavior will change after the pandemic. During the pandemic, 56.8% of employees primarily communicated online and only 21.4% face-to-face. This is similar for leaders (primarily 59.3% digital to 23.2% face-to-face). After the pandemic, the picture reverses: 49.5% of followers expect to communicate predominantly face-to-face and only 20.8% predominantly online. This is similar for leaders (41.3% face-to-face and only 26.6% digital).

Regarding digital communication, synchronous forms (video, telephone) will prevail after the pandemic. This is more pronounced by leaders (44.9% for synchronous communication versus 14.4% for asynchronous communication) than by followers (38.3% versus 21.0%).

C.4) Leaders use online tools for digital leadership

Leaders who also work from home try to support digital collaboration with **digital online tools for conferencing, project management, and informal encounter**. According to their own assessment, 48% work with communication routines such as a joint online meeting at the start of the day or week, e.g., with WebEx, Zoom, MS Teams, and 45% also use digital project management tools to ensure transparency with regard to the tasks and responsibilities of all team or project members (e.g., Jira, Confluence, Asana, Kanban, Trello, MS Planner). From the follower perspective, the percentage is lower at 36% and 25%, respectively.

The promotion of informal contacts and communication is an important issue in digital work. According to their own assessment, 46% leaders promote informal encounters between themselves and employees through virtual afterwork parties, shared lunches or coffee breaks, e.g., with Gathertown. Again, from the employees' perspective, the percentage is lower at 28%. Many leaders (45%) also try to promote direct face-to-face contact under pandemic conditions, e.g., newly formed teams or project groups. From the employees' perspective, the percentage is lower at 27%.

Overall, around 45% of the leaders say they support digital collaboration through various measures and the use of digital tools. Only about 20% do not use any tools or do not explicitly support informal communication. From the perspective of employees, the proportion of leaders who say they support digital collaboration through various measures and the use of digital tools is lower at around 30%. Conversely, around 45% state that their leaders tend not to take any measures.

C.5) Digital leadership pays off

When leaders engage in digital leadership by fostering communication and using digital tools, this has a variety of positive effects for followers and leaders themselves. Employees whose leaders engage in digital leadership experience less stress (r = -.17), more engagement (r = .44), more commitment (r = .47), better health (r = .21), higher job satisfaction (r = .35), and better performance in the HO (r = .16) but also in the office (r = .22).

Leaders who engage in digital leadership themselves experience less stress (r = -.17), more engagement (r = .30), more commitment (r = .29), better health (r = .25), and report a better performance of their employees in the HO (r = .20) but also in the office (r = .21). It is possible that they benefit themselves by leading more effectively and efficiently. However, it is also conceivable that leaders who are less stressed and more motivated are more likely to engage in digital leadership.

Employees whose leaders engage in digital leadership also experience better informal contact when working from home (r = .47). This is also supported from the perspective of the leaders (r = .34).

C.6) Specific challenges for digital leadership

To further identify specific challenges for digital leadership, leaders were asked to directly compare both settings. They report specific problems in the areas of management, control, support, and coordination in the team, in comparison to leadership in the traditional day-to-day office environment.

Above all, 46% leaders find it difficult to **notice when someone needs support** when working from home. In the office, only 22% report this difficulty. It is also more difficult to **recognize employees' current workload** and to see how much employees are actually working. This is experienced as difficult by 42% at home, while this is seen as critical by only 22% in the office. It is challenging to find out whether the team members **coordinate** well with each other. This is experienced as difficult by 41% when working from home, while this is seen as critical by only 20% in the office. 38% report that **spontaneous communication** is difficult (21% in the office) and 36% find it difficult to **learn about problems** in a timely manner (19% in the office) or to find out whether employees have **understood the tasks** correctly (33% in the HO compared to 19% in the office). Furthermore, 24.7% of the leaders report that in the HO it is "difficult to really understand the respective points of view in case of **problems/conflicts** in the team (17.4% in the office). Similarly, when problems/conflicts arise, it is difficult to find solutions with which everyone is satisfied (24.8% in the HO vs. 16.2% in the office).

Although leaders rate their employees' work performance worse in a direct comparison in the HO than in the office, they largely **trust** their employees. For example, 64.6% of leaders with HO state that they "trust their employees to be fully committed to their work even in the home-office and not to exploit the home-office for private purposes". This impression is confirmed by employees (63.6%). However, only 42.0% of employees experience concrete health-promoting support by their leaders in the home-office: "considers environmental conditions in the home-office (technical, family, spatial, etc.)" and "supports that the employees in the home-office have appropriate technical and ergonomic equipment" (37.4%). Even a smaller percentage reports that their leader "notices and reacts when they are not feeling well in the home-office and are tired and fatigued (17.4%) or encourages them to "compensate for this in the home-office by exercising" (22.4%) or to "ensure sufficient healthy nutrition" (18.1%). Comparing the employees' assessments of health-promoting support with the leaders' self-assessment reveals a clear discrepancy: about 50% of the leaders believe that they provide health promotion.

Employees whose leaders offer health-promoting support in the home-office also experience a better informal contact in the HO ($r = .61$), take more care of their own health themselves (SelfCare; $r = .34$). They report fewer health complaints ($r = -.18$), less stress ($r = -.21$), feel better ($r = .32$), are healthier ($r = .24$) and more engaged ($r = .47$), feel more connected to the company ($r = .46$), are more satisfied with their work ($r = .36$).

V. Discussion

On the one side, the results from our survey show that working from home offers opportunities for many employees, in terms of higher autonomy and flexibility, less interruptions and better work-life-balance. Overall, there are positive consequence for commitment, job satisfaction, engagement, and heath. There are also boundary conditions and third variables that may strengthen or weaken the effects, e.g., stronger with voluntariness or weaker for leaders.

On the other side, our findings reveal several risks that should be acknowledged. Among these risks are poorer workplace equipment and technical problems, higher expectations for permanent availability outside working hours, exhausting web conferences with zoom fatigue and isolation. In particular, informal contact und communication is reduced with digital communication. For leaders we identified specific challenges. Most of them result from communication limitations when working from home. For example, leaders find it difficult to recognize critical signs of work overload and conflicts, to assess performance, and to support health.

Employees, leaders, and organizations should be aware of these potential opportunities and risks. Knowledge and awareness are important preconditions to foster resources and to reduce specific risks at all levels. For example, the preference of synchronous rather than asynchronous communication, ensuring regular informal communication, consideration of employees' living conditions at home, the benefit of rules of conduct for availability, avoidance of multitasking during web conferences, or the systematic use of online tools that facilitate communication and cooperation are already helpful strategies to cope with the challenges of digital work and leadership [36].

Nevertheless, further research to improve digital work and leadership is needed. Longitudinal analyses may clarify development over longer periods of time and allow for causal inferences. Experimental studies can isolate single effects of specific settings (e.g., face-to-face vs. online) or online tools (phone vs. video vs. VR) on specific outcomes (health, performance etc.) and also better control for alternative explanations.

From a practical perspective, innovative tools may facilitate digital leadership. Drawing upon the current findings, the authors develop an online platform that can be used simultaneously as a learning tool and as a feedback tool. Both functions may be supportive for an effective and healthy work in a digital setting at home. The learning function fills the gap of lacking information on typical risks and opportunities and provides recommendations for a proper handling for leaders and followers. The feedback function reflects on the limited communication possibilities and will offer devices for systematic and spontaneous feedback. Monitoring the team status over longer periods of time may help acting before things go wrong.

Acknolodgement

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [Digital Leadership and Health].

References

[1] Hans-Böckler-Stiftung, *Neue Verordnung wirkt sich aus - Deutlicher Anstieg: 24 Prozent der Erwerbstätigen arbeiten aktuell vorwiegend oder ausschließlich im Homeoffice.* [Online]. Available: https://www.boeckler.de/pdf/pm_wsi_2021_02_16.pdf (accessed: 20.07.222).

[2] A. Al-Habaibeh, M. Watkins, K. Waried, and M. B. Javareshk, "Challenges and opportunities of remotely working from home during Covid-19 pandemic," *Global Transitions*, vol. 3, pp. 99–108, 2021, doi: 10.1016/j.glt.2021.11.001.

[3] Y. Xiao, B. Becerik-Gerber, G. Lucas, and S. C. Roll, "Impacts of Working From Home During COVID-19 Pandemic on Physical and Mental Well-Being of Office Workstation Users," *Journal of Occupational and Environmental Medicine*, vol. 63, no. 3, pp. 181–190, 2021, doi: 10.1097/JOM.0000000000002097.

[4] K. Kirchner, C. Ipsen, and J. P. Hansen, "COVID-19 leadership challenges in knowledge work," *Knowledge Management Research & Practice*, vol. 19, no. 4, pp. 493–500, 2021, doi: 10.1080/14778238.2021.1877579.

[5] J. E. Hoch and S. W. J. Kozlowski, "Leading virtual teams: hierarchical leadership, structural supports, and shared team leadership," *Journal of Applied Psychology*, vol. 99, no. 3, pp. 390–403, 2014, doi: 10.1037/a0030264.

[6] B. J. Avolio, S. Kahai, and G. E. Dodge, "E-leadership," *Leadership Quarterly*, vol. 11, no. 4, pp. 615–668, 2000, doi: 10.1016/S1048-9843(00)00062-X.

[7] B. S. Bell and S. W. J. Kozlowski, "A Typology of Virtual Teams," *Group & Organization Management*, vol. 27, no. 1, pp. 14–49, 2002, doi: 10.1177/1059601102027001003.

[8] Eurofound, *Telework and ICT-based mobile work: Flexible working in the digital age, New forms of employment series.* [Online]. Available: https://www.eurofound.europa.eu/publications/report/2020/telework-and-ict-based-mobile-work-flexible-working-in-the-digital-age

[9] J. C. Lengen, A.-C. Kordsmeyer, E. Rohwer, V. Harth, and S. Mache, "Soziale Isolation im Homeoffice im Kontext der COVID-19-Pandemie: Hinweise für die Gestaltung von Homeoffice im Hinblick auf soziale Bedürfnisse," (in ger), *Zentralblatt für Arbeitsmedizin, Arbeitsschutz und Ergonomie*, vol. 71, no. 2, pp. 63–68, 2021, doi: 10.1007/s40664-020-00410-w.

[10] Y. Lott, "Work-Life Balance im Homeoffice: Was kann der Betrieb tun?," *WSI Report*, vol. 54, 2020. [Online]. Available: https://www.boeckler.de/pdf/p_wsi_report_54_2020.pdf

[11] M. Amlinger-Chatterjee and A. M. Wöhrmann, "Flexible Arbeitszeiten," *Zeitschrift für Arbeitswissenschaft*, vol. 71, no. 1, pp. 39–51, 2017, doi: 10.1007/s41449-017-0047-x.

[12] A. I. Tavares, "Telework and health effects review," *International Journal of Healthcare*, vol. 3, no. 2, p. 30, 2017, doi: 10.5430/IJH.V3N2P30.

[13] A. M. Wöhrmann, N. Backhaus, A. Tisch, and A. Michel, *BAuA-Arbeitszeitbefragung: Pendeln, Telearbeit, Dienstreisen, wechselnde und mobile Arbeitsorte: Forschung Projekt F 2452,* 1st ed. Dortmund, Berlin, Dresden: Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA), 2020.

[14] Y. Park, C. Fritz, and S. M. Jex, "Relationships between work-home segmentation and psychological detachment from work: the role of communication technology use at home," *Journal of Occupational Health Psychology*, vol. 16, no. 4, pp. 457–467, 2011, doi: 10.1037/a0023594.

[15] P. Standen, "The home/work interface," in *Managing telework: Perspectives from human resource management and work psychology*, K. Daniels, D. Lamond, and P. Standen, Eds., Australia: Business Press, 2000, pp. 83–92.

[16] P. Stevens, "The 2020 Remote Working Employee Survey," *Wildgoose Events*, 02 Jun., 2020. https://wearewildgoose.com/uk/news/the-working-from-home-employee-survey/ (accessed: Apr. 5 2022).

[17] T. Müller and C. Niessen, "Self-leadership and self-control strength in the work context," *Journal of Managerial Psychology*, vol. 33, no. 1, pp. 74–92, 2018. [Online]. Available: https://doi.org/10.1108/JMP-04-2017-0149

[18] R. S. Gajendran and D. A. Harrison, "The good, the bad, and the unknown about telecommuting: meta-analysis of psychological mediators and individual consequences," *Journal of Applied Psychology*, vol. 92, no. 6, pp. 1524–1541, 2007, doi: 10.1037/0021-9010.92.6.1524.

[19] T. Gerding *et al.,* "An assessment of ergonomic issues in the home offices of university employees sent home due to the COVID-19 pandemic," *Work*, vol. 68, no. 4, pp. 981–992, 2021, doi: 10.3233/WOR-205294.

[20] L. Yang *et al.,* "The effects of remote work on collaboration among information workers," *Nature human behaviour*, vol. 6, no. 1, pp. 43–54, 2022, doi: 10.1038/s41562-021-01196-4.

[21] G. Hertel, S. Geister, and U. Konradt, "Managing virtual teams: A review of current empirical research," *Human Resource Management Review*, vol. 15, no. 1, pp. 69–95, 2005, doi: 10.1016/j.hrmr.2005.01.002.

[22] G. Fauville, M. Luo, A. Queiroz, J. N. Bailenson, and J. Hancock, "Zoom Exhaustion & Fatigue Scale," *Computers in Human Behavior Reports*, vol. 4, p. 100119, 2021, doi: 10.1016/j.chbr.2021.100119.

[23] K. A. Karl, J. V. Peluchette, and N. Aghakhani, "Virtual Work Meetings During the COVID-19 Pandemic: The Good, Bad, and Ugly," *Small Group Research*, 104649642110152, 2021, doi: 10.1177/10464964211015286.

[24] L. Fosslien and M. W. Duffy, *How to combat Zoom fatigue. Harvard Business Review.* [Online]. Available: https://hbr.org/2020/04/how-to-combat-zoom-fatigue

[25] T. A. Bentley, S. T. T. Teo, L. McLeod, F. Tan, R. Bosua, and M. Gloet, "The role of organisational support in teleworker wellbeing: a socio-technical systems approach," *Applied Ergonomics*, vol. 52, pp. 207–215, 2016, doi: 10.1016/j.apergo.2015.07.019.

[26] S. R. Sardeshmukh, D. Sharma, and T. D. Golden, "Impact of telework on exhaustion and job engagement: a job demands and job resources model," *New Technology, Work and Employment*, vol. 27, no. 3, pp. 193–207, 2012, doi: 10.1111/J.1468-005X.2012.00284.X.

[27] M. Hermann and F. Cordes, "Homeoffice im Zeichen der Pandemie: Neue Perspektiven für Wissenschaft und Praxis," *IUBH Discussion Papers – Human Resources*, vol. 2, 2020.

[28] M. Charalampous, C. A. Grant, C. Tramontano, and E. Michailidis, "Systematically reviewing remote e-workers' well-being at work: a multidimensional approach," *European Journal of Work and Organizational Psychology*, vol. 28, no. 1, pp. 51–73, 2019, doi: 10.1080/1359432X.2018.1541886.

[29] S. Stegmann *et al.,* "Der Work Design Questionnaire," *Zeitschrift für Arbeits- und Organisationspsychologie A&O*, vol. 54, no. 1, pp. 1–28, 2010, doi: 10.1026/0932-4089/a000002.

[30] J. Dettmers and A. Krause, "Der Fragebogen zur Gefährdungsbeurteilung psychischer Belastungen (FGBU)," *Zeitschrift für Arbeits- und Organisationspsychologie A&O*, vol. 64, no. 2, pp. 99–119, 2020, doi: 10.1026/0932-4089/a000318.

[31] A. Day, S. Paquet, N. Scott, and L. A. Hambley, "Perceived information and communication technology (ICT) demands on employee outcomes: the moderating effect of organizational ICT support," *Journal of Occupational Health Psychology*, vol. 17, no. 4, pp. 473–491, 2012, doi: 10.1037/a0029837.

[32] W. B. Schaufeli, A. Shimazu, J. J. Hakanen, M. Salanova, and H. de Witte, "An Ultra-Short Measure for Work Engagement," *European Journal of Psychological Assessment*, vol. 35, no. 4, pp. 577–591, 2017, doi: 10.1027/1015-5759/a000430.

[33] J. Felfe and F. Franke, *COMMIT Commitment Skalen–Fragebogen zur Erfassung von Commitment gegenüber Organisation, Beruf/Tätigkeit, Team, Führungskraft und Beschäftigungsform*. Bern: Hans Huber, 2012.

[34] G. Mohr, T. Rigotti, and A. Müller, "Irritation Scale. A tool to assess psychological strain in the work context. Scale and item parameters from 15 studies," *Zeitschrift für Arbeits- und Organisationspsychologie*, vol. 49, no. 1, pp. 44–48, 2005, doi: 10.1026/0932-4089.49.1.44.

[35] M. Nübling, U. Stößel, H.-M. Hasselhorn, M. Michaelis, and F. Hofmann, "Measuring psychological stress and strain at work: Evaluation of the COPSOQ Questionnaire in Germany," *GMS Psycho-Social-Medicine*, vol. 3, Doc05, 2006.

[36] A. Krick, J. Felfe, S. M. Neidlinger, D. Tautz, and K.-H. Renner, "Chancen und Risiken des digitalen Arbeitens: Wie man Probleme vermeiden kann," *Betriebliche Prävention: Arbeit / Gesundheit / Unfallversicherung*, vol. 6, no. 134, pp. 269–274, 2022.

Digitale Führung und Gesundheit: Eine Forschungsperspektive

Jörg Felfe[1]*, Sven Hauff[1], Annika Krick[1], Karl-Heinz Renner[2]
[1] *Helmut Schmidt University,* Hamburg, Germany
[2] *Universität der Bundeswehr,* Munich, Germany
*felfe@hsu-hh.de

Kurzfassung **– Die Corona-Pandemie hat einen Schub der Nutzung digitaler und virtueller Arbeits- und Führungsstrukturen bewirkt (Remote Work, Homeoffice, Videokonferenzen etc.) und es ist zu erwarten, dass diese auch zukünftig zunehmend die Arbeitswelt charakterisieren werden. Ziel des in diesem Beitrag vorgestellten Forschungsvorhabens „Digital Leadership and Health“ ist es mittels mehrerer empirischer Studien, 1) Konsequenzen digitaler und virtueller Arbeitsformen für die Leistung und Motivation sowie Gesundheit der Beschäftigten zu erforschen sowie 2) förderliche und hinderliche Gestaltungsoptionen für eine effektive und nachhaltige Nutzung von digitalen Arbeitsformen unter besonderer Berücksichtigung von Gesundheitsförderung, Führung und HRM Strategien zu identifizieren. Mit Hilfe der gewonnenen Erkenntnisse werden 3) praktische Lösungsansätze für eine effektive und nachhaltige Nutzung digitaler Arbeitsformen entwickelt und erprobt (technische Hinweise, Verhaltensregeln für Führungskräfte und Beschäftigte). Als zentrales Tool soll eine Erhebungs- und Feedbackplattform entwickelt werden, mit deren Hilfe Unternehmen schnell und einfach die konkrete Umsetzung von Homeoffice und digitalen Arbeitsformen und die damit verbundenen Folgen evaluieren können.**

Stichworte – Digital Leadership, Health-oriented Leadership, Gesundheitsförderung, Homeoffice, Arbeitszufriedenheit, Commitment, Personalmanagementstrategien, High-performance Work Practices (HPWPs), Well-being-oriented HRM

I. Einleitung

Die Corona-Pandemie hat die Nutzung digitaler und virtueller Arbeits- und Führungsstrukturen erheblich befördert (Remote Work, Homeoffice, Videokonferenzen etc.). Es ist zu erwarten, dass diese digitalen Arbeits- und Führungsstrukturen auch zukünftig zunehmend die Arbeitswelt charakterisieren werden. Umfragen deuten darauf hin, dass diese Flexibilisierung traditioneller Arbeitsformen die Krise überleben dürfte. So sagten 67 Prozent von 7300 befragten Firmen dem Ifo-Institut, dass sie langfristig mehr Homeoffice nutzen wollen [1]. Ähnliches zeigt eine Umfrage der Hans-Böckler-Stiftung: 71% der Befragten geben an, dass Homeoffice in Zukunft weiter verbreitet sein wird [2]. Laut Spiegel plant zum Beispiel Siemens 2 bis 3 Tage Homeoffice für allein 45.000 Beschäftigte in Deutschland. Damit verbunden wird auch ein anderer Führungsstil erwartet, der sich an Ergebnissen und nicht an der Präsenz im Büro orientiert (Spiegel/16.7.2020).

Mit der verstärkten Nutzung von Homeoffice sind für die Beschäftigten Chancen (z. B. Flexibilisierung, bessere Work-Life-Balance), aber auch erhebliche Risiken (z. B. Entgrenzung, Isolation) verbunden. Längerfristige Auswirkungen auf die psychische Gesundheit aber auch auf Bindung und Identifikation (Commitment, Zusammenhalt) sind bislang aber eher unbekannt. Aus Sicht der Unternehmen und Führungskräfte stehen den Chancen (z. B. Einsparpotenziale in den Bereichen Reisekosten, Bürokosten), ebenfalls Risiken gegenüber. Hierzu gehören insbesondere Verunsicherungen, wie zentrale Führungsstrukturen und -funktionen (Motivation, Kontrolle, Teamentwicklung, Mitarbeiterförderung, Gesundheitsförderung etc.) dauerhaft auf Distanz in Form von Digital und Virtual Leadership wahrgenommen werden können. Insgesamt sind die Auswirkungen einer konsequenten Nutzung digitaler und virtueller Arbeits- und Führungsstrukturen nach wie vor nicht umfassend erforscht. Hier bedarf es systematischer empirischer Untersuchungen, um die aktuelle Entwicklung zuverlässig zu begleiten.

Ziel des hier vorgestellten Forschungsvorhabens („Digital Leadership and Health“) ist es daher, förderliche und hinderliche Bedingungen sowie Lösungen für eine effektive und nachhaltige Nutzung von digitalen und virtuellen Arbeitsformen, insbesondere Homeoffice, unter besonderer Berücksichtigung von Gesundheitsförderung und Führung zu erforschen und praktische Lösungsansätze (Online Tools, Trainings, Handreichungen) zu entwickeln. Die jeweiligen Erkenntnisse und Lösungsansätze sollen Führungskräfte und Beschäftigte unterschiedlichster Unternehmen und Organisationen (Versicherungswirtschaft, Finanzwirtschaft, Industrie, Handel aber auch öffentliche Verwaltungen und Hochschulen etc.), die bereits in hohem Maße digitale und virtuelle Arbeits- und Führungsstrukturen einsetzen bzw. künftig verstärkt einsetzen wollen, unterstützen. Im Folgenden werden Forschungshintergrund, Forschungsfragen und die methodische Umsetzung näher erläutert.

II. Chancen und Risiken digitaler Arbeit und Führung

Durch die Corona-Pandemie haben digitale und virtuelle Arbeits- und Führungsstrukturen (Homeoffice, Videokonferenzen etc.) einen enormen Bedeutungszuwachs erfahren [1, 2]. Momentan ist zwar noch unklar, inwieweit künftig wieder zu alten, klassischen Arbeitsformen zurückgekehrt wird. Zu erwarten ist, dass digitale und virtuelle Arbeits- und Führungsstrukturen die Arbeitswelt auch zukünftig zunehmend charakterisieren werden [1, 2]. Der Ermöglichung und Nutzung von Homeoffice für weite Teile der Beschäftigten, die bislang überwiegend im Büro tätig waren, wird dabei eine zentrale Bedeutung zukommen.

https://doi.org/10.24405/14575

Durch die Nutzung von Homeoffice ergeben sich für die Beschäftigten Chancen, aber auch Risiken. Auf der einen Seite stehen zeitlich und räumliche Flexibilisierung, Vereinbarkeit von Arbeit und Privatleben bzw. Familie (Work-Life-Balance), Einsparung von Mobilitätskosten etc. Auf der anderen Seite stehen Entgrenzung, Verlust an zeitlicher und räumlicher Struktur, Verlust informeller sozialer Kontakte (Isolation), Regulationshindernisse bei Kommunikation sowie verminderte Kooperation und Information [3–7]. Soziale Nachteile (Isolation, Zugehörigkeit zum Team) scheinen vor allem dann zu entstehen, wenn Homeoffice intensiver genutzt wird (> 2 Tage die Woche) [3, 7]. Damit einher gehen potenzielle längerfristige Auswirkungen auf die psychische Gesundheit, aber auch auf Bindung und Identifikation (Commitment, Zusammenhalt), welche bislang wenig erforscht sind.

Aus Sicht der Unternehmen und Führungskräfte stehen den Chancen, die durch Einsparpotenziale in den Bereichen Reisekosten, Bürokosten, Beschleunigung von Abstimmungs- und Kooperationsprozessen erzielt werden können, ebenfalls Risiken gegenüber. Hierzu gehören insbesondere Verunsicherungen auf Seiten der verantwortlichen Geschäftsleitungen und Führungskräfte bezüglich der Frage, wie zentrale Führungsstrukturen und -funktionen (z. B. Motivation, Kontrolle, Teamentwicklung, Mitarbeiterförderung oder Gesundheitsförderung) dauerhaft in Form von Digital Leadership wahrgenommen werden können.

Ähnlich ambivalent stellt sich die Situation in Bezug auf Videokonferenzen dar, die zunehmend die traditionelle Meetingkultur in Präsenz ablösen. Auf der einen Seite werden Effektivitätssteigerungen berichtet. Videokonferenzen lassen sich zeitlich enger takten, Reise- und Organisationsaufwand werden reduziert und die Beteiligten kommen schneller zur Sache, da weniger Zeit mit informellen Gesprächen am Rande verbracht wird. Auf der anderen Seite wird der Verlust informeller Kommunikation beklagt und darin Risiken für die Vertrauensbildung und den Zusammenhalt im Team gesehen. Zudem wird Multitasking (z. B. simultane Teilnahme an mehreren Videokonferenzen oder parallele Beantwortung von Mails) als Risiko erkannt. Die Doppelbelastung erhöht das Risiko von psychischem Stress, Fehlern und Qualitätseinbußen, wenn die Aufmerksamkeit nicht konzentriert, sondern geteilt ist. Für diese spezifische Form des Stresserlebens hat sich bereits der Begriff der „Zoom fatigue“ etabliert [8, 9].

Um diesen Herausforderungen künftig erfolgreich begegnen zu können, sind nachhaltige Gestaltungsansätze und Kompetenzen zu entwickeln, die zum einen technische und organisatorische Potenziale sowie interaktionale und kommunikative Kompetenzen (Führung, Selbstmanagement), zum anderen aber auch Konsequenzen für Leistung (z. B. Techno-Work Engagement; [10] und die Gesundheit der Beschäftigten berücksichtigen.

Digitale und virtuelle Arbeits- und Führungsstrukturen stellen Veränderungen von Arbeitsbedingungen dar, die sich im Rahmen des etablierten Job Demands-Resources (JD-R) Modells [11], dass als theoretischer Rahmen des Vorhabens dient, als Belastungen (Job Demands) oder Ressourcen modellieren lassen. Belastungen wirken sich negativ auf Leistung, Zufriedenheit und Motivation aus, während Ressourcen positiv wirken. Spezifische IT bezogene Belastungen werden in der Literatur als “ICT demands” bezeichnet [12, 13]. Hierzu zählen unter anderem „hassles using ICT“ (technische Probleme), „response expectations“ (Erwartung schneller Reaktionen), „availability expectations“ (Erwartung stetiger Erreichbarkeit), Workload (Erhöhung der Arbeitsmenge durch mehr Flexiblität), „ICT learning expectations“ (Erwartungen an den Erwerb digitaler Kompetenzen), „ineffective communication“ (Risiko und Zunahme von Missverständnissen) sowie „employee monitoring“ (Herausforderungen bei der Leistungsüberwachung) [12].

Ressourcen können die negativen Auswirkungen derartiger Belastungen puffern bzw. reduzieren. Soziale Unterstützung durch Kollegen*innen und Vorgesetzte, organisationale Unterstützung im Rahmen von Human Resource Management, vor allem aber auch positive Führung im Sinne transformationaler Führung oder gesundheitsförderlicher Führung werden üblicherweise als zentrale Ressourcen gezählt [14–21]). Im vorliegenden Fall digitaler Arbeit wird Führung aber selbst durch digitale und virtuelle Strukturen verändert und ggf. eingeschränkt. Damit besteht unter Umständen ein doppeltes Risiko, da nicht nur die unmittelbaren Belastungsfolgen abgeschätzt werden müssen, sondern auch der Verlust relevanter Ressourcen einzukalkulieren ist. Diese Risiken und Dynamiken gilt es zu analysieren, um geeignete Maßnahmen ableiten zu können.

Die Forschung unterstreicht beispielsweise die Rolle der technischen Ausstattung, des organisationalen Supports und der digitalen Kompetenz des Individuums, die sich auf das Wohlbefinden der Beschäftigten auswirken können [22, 23]. Darüber hinaus können aber auch weitere Situationsmerkmale (organizational ICT support [12], familiäre Doppelbelastung, Arbeitsaufgabe, Handlungsspielraum, Persönlichkeitsmerkmale (Core Self-Evaluations, Locus of control, Self-efficacy, Openness, Ambiguitätstolranz, Medienkompetenz) und Einstellungen eine Rolle spielen [24]. Bislang gibt es in der Literatur zwar einige Hinweise zu Risiken und Maßnahmen im Umgang mit digitalen Arbeitsformen, die empirisch aber kaum untermauert sind und vor allem davon ausgehen, dass Homeoffice eher die Ausnahme als die Regel ist.

Hinsichtlich digitaler und virtueller Führung finden sich ebenfalls erste Hinweise, dass digitale und virtuelle Führung vielfältige Herausforderungen für Führungskräfte mit sich bringen (z. B. [25, 26]). So ist gerade die berufliche Isolation von Mitarbeitenden ein bekanntes Problem [27, 28], mit dem sich Führungskräfte auseinandersetzen setzen müssen. Hierfür sind neue Formen der Unterstützung sowie eine Anpassung der Unternehmenskultur nötig [29]. Bei der Leitung virtueller Teams ist darauf zu achten, dass zumindest beim Start der Zusammenarbeit Präsenzphasen ermöglicht werden sollten, um persönliche Kontakte aufzubauen. Werden im weiteren Verlauf überwiegend Webkonferenzen genutzt, ist besonders auf eine sorgfältige und gut strukturierte Kommunikation zu achten. Fehlendes Feedback, Unterbrechung durch Übertragungsprobleme etc. führen leichter zu Verständnisschwierigkeiten und Missverständnissen, deren Konsequenzen sich erst in der weiteren Zusammenarbeit zeigen und dann zu Konflikten führen.

Stellten Homeoffice und digitale Arbeitsformen bislang eher eine ergänzende, wenn auch zunehmend häufiger genutzte Alternative zu überwiegend auf Präsenz ausgelegte Arbeitsformen (z. B. 1 Tag Homeoffice Regelungen) dar oder waren auf bestimmte Bereiche außerhalb traditioneller Beschäftigungsverhältnisse beschränkt (Click Work, Crowd Work), wurden Homeoffice sowie digitale und virtuelle Führung in der Corona-Krise zum verbreiteten Standard. Damit bietet sich gerade die Chance einer systematischen empirischen „Begleitforschung" der aktuellen Situation bzw. der zurückliegenden Erfahrungen, wenn wieder verstärkt zu Präsenz zurückgekehrt wird. Es ist jedoch davon auszugehen, dass Homeoffice auch künftig umfassender genutzt wird. Praktiken und Erfahrungen können daher breitflächig und branchenübergreifend systematisch erhoben und aufbereitet werden.

III. Forschungsfragen und Empfehlungen

Vor diesem Hintergrund sollen insbesondere folgende Forschungsfragen bearbeitet und konkrete Entwicklungen vorangetrieben werden, die zum einen aus wissenschaftlicher Sicht, zum anderen aber auch aus Anwendungsperspektive für Unternehmen und Organisationen relevant sind:

A. *Wie wirken sich digitale und virtuelle Arbeitsformen, insbesondere Homeoffice auf die Beschäftigten und Führungskräfte aus?*

- Welche Chancen (z. B. Autonomie, Flexibilität) und Risiken (Entgrenzung, soziale Isolation, informationale Behinderungen) ergeben sich für die Beschäftigten in Bezug auf a) Leistung, Kooperation, b) Zufriedenheit, Commitment und Identifikation, c) Work-Life Balance (WLB) und Gesundheit?
- Welche Chancen und Risiken ergeben sich für die Führungskräfte in Bezug auf a) Führungsverhaltem, b) Zufriedenheit, Commitment und Identifikation, c) Work-Life Balance (WLB) und Gesundheit?

B. *Wie wirken sich digitale und virtuelle Arbeitsformen auf die Mitarbeiterführung aus?*

- Welche Chancen und Risiken ergeben sich für transformationale Führung?
- Welche Chancen und Risiken ergeben sich für gesundheitsförderliche Führung?
- Welche Chancen und Risiken ergeben sich für Personalmanagementstrategien (High-performance Work Practices (HPWPs), Well-being-oriented HRM)?

C. *Welche Faktoren beeinflussen (verstärken oder puffern) die Auswirkungen digitaler und virtueller Arbeitsformen auf die Beschäftigten?*

- Inwieweit können Risiken durch transformationale Führung abgeschwächt werden?
- Inwieweit können Risiken durch gesundheitsförderliche Führung abgeschwächt werden?
- Inwieweit können Risiken durch technische und arbeitsorganisatorische Lösungen abgeschwächt werden?
- Inwieweit können Risiken durch geeignete Personalmanagementstrategien abgeschwächt werden?

Darüber hinaus ist es Ziel des Vorhabens, auf Grundlage dieser Erkenntnisse Maßnahmen für eine effektive und nachhaltige Nutzung von Homeoffice und virtuellen Arbeitsformen unter besonderer Berücksichtigung von Gesundheitsförderung und Führung zu erforschen und praktische Lösungsansätze (Online Tools, Trainings, Handreichungen) zu entwickeln. Hierbei stehen folgende Fragen im Vordergrund:

- Wie können Beschäftigte selbst Chancen konsequenter nutzen und Risiken vermeiden?
- Wie können Führungskräfte Chancen konsequenter nutzen und Risiken vermeiden?
- Durch Schaffung welcher Rahmenbedingungen können Unternehmen Risiken abmildern?
- Wie müssen bisherige Personalmanagementstrategien (z.B. High-performance Work Practices) angepasst werden, damit sie auf digitale und virtuelle Führung abgestimmt sind?

Zu den möglichen Maßnahmen zählen 1) die Entwicklung von konkreten Management-Tools/Führungsinstrumenten, 2) Handreichungen, Checklisten, Handlungsanweisungen für den Führungsalltag, 3) ein Online-Führungskräftetraining zur gesundheitsförderlichen Nutzung digitaler Arbeitsformen sowie 4) die Entwicklung einer digitalen Erhebungs- und Feedback-Plattform.

Mit Hilfe der digitalen Erhebungs- und Feedback-Plattform können Führungskräfte und Beschäftigte Online-Diagnosen und Feedback zu unterschiedlichen Themen und Fragestellungen unmittelbar realisieren (Ampel, Profile, Empfehlungen), um die durch Distanz erschwerten Kommunikations- und Feedbackprozesse effizienter zu ermöglichen. Bislang sind hierzu mehrere getrennte Prozessschritte erforderlich (Erhebung Unipark, Auswertung SPSS, Ergebnisdarstellung PPT, Rückmeldung), welche Unternehmen oft nicht selbst leisten können. Durch die im Rahmen des Projekts zu entwickelnde digitale Erhebungs- und Feedback-Plattform soll ein vollständig integriertes Instrument zu Verfügung gestellt werden, welches in unterschiedlichsten Bereichen (Entscheidungsfindung, Motivation, Gesundheit, Self-Assessment, Evaluation) nutzbar ist. Unternehmen können so ihre aktuelle Situation erfassen und analysieren, um in Verbindung mit den Handlungsempfehlungen konkrete Maßnahmen ableiten zu können. Mit Hilfe dieser digitalen Erhebungs- und Feedbackplattform sollen Unternehmen und Organisationen insbesondere in die Lage versetzt werden, auch für weitere unterschiedliche Anwendungsbereiche effektive Befragungsprozeduren zu realisieren und unmittelbare Auswertungen auf unterschiedlichen Ebenen zu generieren. Damit lassen sich betriebliche Arbeits- und Führungsstrukturen effektiv und schnell analysieren.

Die Erkenntnisse und Lösungsansätze des Projekts können von Führungskräften und Beschäftigten unterschiedlichster Unternehmen und Organisationen (Versicherungswirtschaft, Finanzwirtschaft, Industrie, Handel aber auch öffentliche Verwaltungen, Hochschulen etc.), die bereits in hohem Maße digitale Arbeitsformen einsetzen bzw. verstärkt einsetzen wollen, genutzt werden.

IV. Meilensteine

Zur Erreichung der Projektziele sind mehrere Schritte (Arbeitspakete und Milestones) erforderlich. Auf der Grundlage einer ausführlichen Literaturrecherche (M 1) erfolgt die Konzipierung und Planung der Studien (1. repräsentative Befragung, 2. experimentelle Studien im Simulationslabor) (M 2). Für die Realisierung der experimentellen Studien ist die Planung und Einrichtung von Simulationslaboren erforderlich (M 3). Anschließend erfolgt die Akquisition von Partnerunternehmen für gezielte Interviews und spätere Erprobung von Maßnahmen sowie die Auswahl eines externen Befragungsinstituts (M 4). Bei den Meilensteinen (M 5 und M 6) handelt es sich um die Durchführung der unterschiedlichen Studien. Danach folgen Auswertung und Bericht (M 7) sowie die Ableitung von Handlungsempfehlungen und die Entwicklung einer digitalen Erhebungs- und Feedback-Plattform (M 8). Bereits frühzeitig werden (Teil-)Ergebnisse auf nationalen und internationalen Tagungen präsentiert und mit der Erstellung von Publikationen begonnen (M 9).

Im Folgenden sind alle Meilensteine noch einmal im Detail dargestellt:

M 1: Zur Literaturrecherche gehören aktuelle Recherchen in einschlägigen Datenbanken und Foren. Darüber hinaus werden in Experteninterviews und mit Hilfe von Fokusgruppen Interviews in Unternehmen und Verwaltungen Bedingungen und Faktoren identifiziert, die die Nutzung digitaler Arbeitsformen erleichtern bzw. erschweren. Diese Erkenntnisse (z. B. Nutzung von Web-Tools, Kommunikations- und Moderationsregeln in Web-Konferenzen und Online Mitarbeiter-Gesprächen) werden in den folgenden Schritten für die Konkretisierung und Präzisierung der Studien genutzt.

M 2: Zur Konzipierung und Planung der Studien zählen die Entwicklung eines vorläufigen theoretischen Rahmens sowie die Auswahl der Untersuchungsvariablen, der Instrumente, Operationalisierungen sowie die Planung der Studiendesigns.

M 2.1. Über mehrerer Messzeitpunkte soll eine annähernd repräsentative Stichprobe wiederholt befragt werden. Um die oben genannten Fragestellungen beantworten zu können, sollen Merkmale der Arbeit, insbesondere Ausprägungen digitaler und virtueller Arbeitsformen (z. B. Homeoffice, Webkonferenzen), Merkmale der Mitarbeiterführung, insbesondere gesundheitsförderliche Führung, und Merkmale des Erlebens und Verhaltens der Beschäftigten (a) Leistung, Kooperation, b) Zufriedenheit, Commitment und Identifikation, c) Work-Life Balance (WLB) und Gesundheit) erhoben werden, um Zusammenhänge zu prüfen.

M 2.2. Mit Hilfe kontrollierter experimenteller Bedingungen mit Kontrollgruppendesign, sollen die Auswirkungen von unterschiedlichen digitalen Arbeitsbedingungen (z. B. Nutzung von Mail (Kontrollbedingung), Webkonferenzsystemen (Multitasking), Aufgabentypen (z.B. Mitarbeitergespräch) sowie von unterschiedlichen Führungsstilen (gesundheitsförderliche Führung) auf das Erleben und Verhalten der Beschäftigten (a) Leistung, Kooperation, b) Zufriedenheit, Commitment und Identifikation, hinsichtlich kausaler Einflüsse) untersucht werden.

M 3: Zur Durchführung der experimentellen Studien wird ein Simulationslabor eingerichtet, in dem Teams und Führungskräfte unter verschiedenen digitalen Arbeitsbedingungen unterschiedliche Aufgaben gemeinsam bewältigen sollen.

M 4: Für Interviews und die Erprobung von Maßnahmen werden Partnerunternehmen akquiriert.

M 5: Die zu erwartenden Ergebnisse der repräsentativen Befragung zu mehreren Zeitpunkten sollen zeigen, wie sich unterschiedliche Formen digitaler Arbeit und Führung längerfristig auf Leistung und Erleben der Beschäftigten auswirken.

M 6: Die zu erwartenden Ergebnisse der experimentellen Simulationsstudien sollen kausale Effekte unterschiedlicher Formen digitaler Arbeit und Führung in einem kontrollierten Setting belegen.

M 7: Die Auswertung der Befragungsdaten erfolgt sukzessive im Laufe des Datenerhebungsprozesses und nach dessen Abschluss. Bei den Befragungsdaten werden sowohl Querschnittanalysen der jeweiligen Teildatensätze als auch Längsschnittanalysen durchgeführt. Darüber hinaus sollen innovative Verfahren wie die Necessary Condition Analysis (NCA) zum Einsatz kommen. Die NCA scheint gerade für die im Rahmen des Projekts avisierten Fragen vielversprechend. So kann z. B. identifiziert werden, welches Führungsverhalten notwendig bzw. kritisch (im Sinne eines Must-Have-Faktors) ist, um das Wohlbefinden der Beschäftigten nicht zu gefährden und negative Folgewirkungen von Homeoffice zu unterbinden.

M 8: Die zu entwickelnden Handlungsempfehlungen beziehen sich auf einen effizienten Einsatz digitaler Arbeitsformen (Regeln für Webkonferenzen, für die Gesprächsführung in Online-Mitarbeitergesprächen, für die Nutzung der Feedback-Plattform, für die Arbeitsorganisation). Die Regelwerke sollen technische Hinweise für eine effiziente Nutzung, vor allem aber Verhaltensregeln für Führungskräfte und Beschäftigte beinhalten. Die Entwicklung erfolgt auf Basis der in den Interviews und Experimenten ermittelten Chancen und Risiken digitaler Arbeitsformen für die Leistung und das Erleben von Beschäftigten und Teams. Als zentrales Tool soll eine Erhebungs- und Feedbackplattform entwickelt werden, mit deren Hilfe Unternehmen schnell und einfach die konkrete Umsetzung von Homeoffice und digitalen Arbeitsformen und die damit impliziteren Folgen evaluieren können. Die Erhebungs- und Feedbackplattform soll eine modulare Struktur haben, so dass unterschiedliche Themenbereiche (Führung, Digitalisierung, Leistung und Gesundheit) gezielt ausgewählt werden können. Eine automatisierte Auswertung soll in Verbindung mit den Handlungsempfehlungen Ansätze für konkrete Maßnahmen zur eventuellen Verbesserung der Situation liefern. Die Feedbackplattform wird von einem externen Partner entwickelt und bereitgestellt. Hierfür sind Investitionskosten und Unteraufträge einzukalkulieren.

M 9: Die Forschungsergebnisse sollen frühzeitig auf nationalen und internationalen Fachkonferenzen vorgestellt werden. Darauf aufbauend sind mehrere Publikationen in internationalen Fachzeitschriften vorgesehen.

DANKSAGUNG

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Digital Leadership and Health].

LITERATUR

[1] K. Demmelhuber, F. Englmaier, F. Leiss, S. Möhrle, A. Peichl, and T. Schröter, “Homeoffice vor und nach Corona: Auswirkungen und Geschlechterbetroffenheit,” *Ifo Schnelldienst digital*, vol. 14, 01-04, 2020. [Online]. Available: https://www.ifo.de/publikationen/2020/aufsatz-zeitschrift/homeoffice-vor-und-nach-corona-auswirkungen-und

[2] Hans-Böckler-Stiftung, *Studien zu Homeoffice und mobiler Arbeit.* [Online]. Available: https://www.boeckler.de/de/auf-einen-blick-17945-Auf-einen-Blick-Studien-zu-Homeoffice-und-mobiler-Arbeit-28040.htm

[3] N. Backhaus, A. M. Wöhrmann, and A. Tisch, *BAuA-Arbeitszeitbefragung: Telearbeit in Deutschland.* [Online]. Available: https://www.baua.de/DE/Angebote/Publikationen/Bericht-kompakt/Telearbeit.pdf?__blob=publicationFile&v=4

[4] J. C. Lengen, A.-C. Kordsmeyer, E. Rohwer, V. Harth, and S. Mache, “Soziale Isolation im Homeoffice im Kontext der COVID-19-

Pandemie: Hinweise für die Gestaltung von Homeoffice im Hinblick auf soziale Bedürfnisse," (in ger), *Zentralblatt für Arbeitsmedizin, Arbeitsschutz und Ergonomie*, vol. 71, no. 2, pp. 63–68, 2021, doi: 10.1007/s40664-020-00410-w.

[5] Y. Lott, "Work-Life Balance im Homeoffice: Was kann der Betrieb tun?," *WSI Report*, vol. 54, 2020. [Online]. Available: https://www.boeckler.de/pdf/p_wsi_report_54_2020.pdf

[6] S. Kauffeld, L. Handke, and J. Straube, "Verteilt und doch verbunden: Virtuelle Teamarbeit," *Gruppe. Interaktion. Organisation. Zeitschrift für Angewandte Organisationspsychologie (GIO)*, vol. 47, no. 1, pp. 43–51, 2016, doi: 10.1007/s11612-016-0308-8.

[7] R. S. Gajendran and D. A. Harrison, "The good, the bad, and the unknown about telecommuting: meta-analysis of psychological mediators and individual consequences," *Journal of Applied Psychology*, vol. 92, no. 6, pp. 1524–1541, 2007, doi: 10.1037/0021-9010.92.6.1524.

[8] J. N. Bailenson, "Nonverbal overload: A theoretical argument for the causes of Zoom fatigue," *Technology, Mind, and Behavior*, vol. 2, no. 1, 2021, doi: 10.1037/tmb0000030.

[9] G. Fauville, M. Luo, A. C. M. Queiroz, J. N. Bailenson, and J. Hancock, "Nonverbal Mechanisms Predict Zoom Fatigue and Explain Why Women Experience Higher Levels than Men," *SSRN Electronic Journal*, 2021, doi: 10.2139/ssrn.3820035.

[10] J.-P. Mäkiniemi, S. Ahola, and J. Joensuu, "A Novel Construct To Measure Employees' Technology-Related Experiences of Well-Being: Empirical Validation of the Techno-Work Engagement Scale (TechnoWES)," *Scandinavian Journal of Work and Organizational Psychology*, vol. 5, no. 1, 2020, doi: 10.16993/sjwop.79.

[11] A. B. Bakker and E. Demerouti, "The Job Demands‐Resources model: state of the art," *Journal of Managerial Psychology*, vol. 22, no. 3, pp. 309–328, 2007, doi: 10.1108/02683940710733115.

[12] A. Day, S. Paquet, N. Scott, and L. A. Hambley, "Perceived information and communication technology (ICT) demands on employee outcomes: the moderating effect of organizational ICT support," *Journal of Occupational Health Psychology*, vol. 17, no. 4, pp. 473–491, 2012, doi: 10.1037/a0029837.

[13] A. Day, N. Scott, and E. Kevin Kelloway, "Information and communication technology: Implications for job stress and employee well-being," in *Research in Occupational Stress and Well-being, New Developments in Theoretical and Conceptual Approaches to Job Stress: Research in Occupational Stress and Well Being Vol 8*, P. L. Perrewe and D. C. Ganster, Eds.: Emerald Publishing Limited, 2010, pp. 317–350.

[14] K. Klug, J. Felfe, and A. Krick, "Caring for Oneself or for Others? How Consistent and Inconsistent Profiles of Health-Oriented Leadership Are Related to Follower Strain and Health," *Frontiers in Psychology*, vol. 10, p. 2456, 2019, doi: 10.3389/fpsyg.2019.02456.

[15] E. Straus, L. Uhlig, J. Kühnel, and C. Korunka, "Remote workers' well-being, perceived productivity, and engagement: which resources should HRM improve during COVID-19? A longitudinal diary study," *International Journal of Human Resource Management*, pp. 1–31, 2022, doi: 10.1080/09585192.2022.2075235.

[16] N. Günther, S. Hauff, and P. Gubernator, "The joint role of HRM and leadership for teleworker well-being: An analysis during the COVID-19 pandemic," *German Journal of Human Resource Management: Zeitschrift für Personalforschung*, vol. 36, no. 3, pp. 353–379, 2022, doi: 10.1177/23970022221083694.

[17] A. A. Katou, M. Koupkas, and E. Triantafillidou, "Job demands-resources model, transformational leadership and organizational performance: a multilevel study," *International Journal of Productivity and Performance Management*, vol. 71, no. 7, pp. 2704–2722, 2022, doi: 10.1108/IJPPM-06-2020-0342.

[18] S. G. Abbasi, "Leadership styles: Moderating impact on job stress and health," *Journal of Human Resources Management Research*, Vol. 2018, ID 322892, pp. 1–12, 2018, doi: 10.5171/2018.322892.

[19] C. J. Syrek, E. Apostel, and C. H. Antoni, "Stress in highly demanding IT jobs: transformational leadership moderates the impact of time pressure on exhaustion and work-life balance," *Journal of Occupational Health Psychology*, vol. 18, no. 3, pp. 252–261, 2013, doi: 10.1037/a0033085.

[20] A. Krick, J. Felfe, and S. Pischel, "Health-oriented leadership as a job resource: can staff care buffer the effects of job demands on employee health and job satisfaction?," *Journal of Managerial Psychology*, vol. 37, no. 2, pp. 139–152, 2022, doi: 10.1108/JMP-02-2021-0067.

[21] A. Khalid, G. Murtaza, A. Zafar, M. A. Zafar, L. Saqib, and R. Mushtaq, "Role of Supportive Leadership as a Moderator between Job Stress and Job Performance," *Information Management and Business Review*, vol. 4, no. 9, pp. 487–495, 2012, doi: 10.22610/imbr.v4i9.1004.

[22] T. A. Bentley, S. T. T. Teo, L. McLeod, F. Tan, R. Bosua, and M. Gloet, "The role of organisational support in teleworker wellbeing: a socio-technical systems approach," *Applied Ergonomics*, vol. 52, pp. 207–215, 2016, doi: 10.1016/j.apergo.2015.07.019.

[23] Y. Wang and N. Haggerty, "Individual Virtual Competence and Its Influence on Work Outcomes," *Journal of Management Information Systems*, vol. 27, no. 4, pp. 299–334, 2011, doi: 10.2753/MIS0742-1222270410.

[24] M. Charalampous, C. A. Grant, C. Tramontano, and E. Michailidis, "Systematically reviewing remote e-workers' well-being at work: a multidimensional approach," *European Journal of Work and Organizational Psychology*, vol. 28, no. 1, pp. 51–73, 2019, doi: 10.1080/1359432X.2018.1541886.

[25] S. Park and Y. J. Cho, "Does telework status affect the behavior and perception of supervisors? Examining task behavior and perception in the telework context," *International Journal of Human Resource Management*, pp. 1–26, 2020, doi: 10.1080/09585192.2020.1777183.

[26] L. Cortellazzo, E. Bruni, and R. Zampieri, "The Role of Leadership in a Digitalized World: A Review," *Frontiers in Psychology*, vol. 10, p. 1938, 2019, doi: 10.3389/fpsyg.2019.01938.

[27] T. D. Golden, J. F. Veiga, and R. N. Dino, "The impact of professional isolation on teleworker job performance and turnover intentions: does time spent teleworking, interacting face-to-face, or having access to communication-enhancing technology matter?," *Journal of Applied Psychology*, vol. 93, no. 6, pp. 1412–1421, 2008, doi: 10.1037/a0012722.

[28] C. D. Cooper and N. B. Kurland, "Telecommuting, professional isolation, and employee development in public and private organizations," *Journal of Organizational Behavior*, vol. 23, no. 4, pp. 511–532, 2002, doi: 10.1002/job.145.

[29] T. D. Allen, T. D. Golden, and K. M. Shockley, "How Effective Is Telecommuting? Assessing the Status of Our Scientific Findings," *Psychological Science in the Public Interest*, vol. 16, no. 2, pp. 40–68, 2015, doi: 10.1177/1529100615593273.

Health-oriented Leadership in a Digital World: A Literature Review and a Research Agenda

Annika Krick*, Jörg Felfe
Helmut Schmidt University, Hamburg, Germany
*krick@hsu-hh.de

***Abstract* – In the course of the Covid 19 pandemic, many employees had to work from home. In addition to opportunities and risks for all employees, working from home also brings special challenges for leaders. In recent years, workplace health promotion has gained enormous importance due to the increase in work demands and a rise in mental illnesses. Leadership also plays an essential role in maintaining health in the workplace. The concept of Health-oriented Leadership (HoL) was developed as a health-specific leadership concept describing how leaders can promote employees' health (Franke et al., 2014). Up to now, previous literature has mainly focused on HoL in traditional work contexts, but less is known for the digital context. The purpose of the present article is to provide a literature review of Health-oriented Leadership in both traditional and digital work context. Moreover, key research gaps for Health-oriented Leadership in the digital context will be identified.**

Keyword – Health-oriented Leadership, occupational health, working from home, health promotion

I. INTRODUCTION

As a result of the Covid-19 pandemic, many employees had to transfer their work from the traditional office to their home. Although working from home has already gradually increased in previous years, driven in particular by technological developments, it was still the exception for most employees [1]. Since the outburst of the Covid-19 pandemic working from home has become the regular normal [2].

For employees, working from home brings opportunities, but also risks. On the one hand, there may be advantages of greater flexibility in terms of time and workplace, more autonomy, time savings due to the omission of commuting to work, and a better work-life balance. On the other hand, there may be risks like constant availability, loss of temporal and spatial structure, loss of informal social contacts, and communication barriers. This is accompanied by potential long-term effects on mental and physical health.

Research on effects of working from home on health is inconsistent so far. Tavares [3] emphasizes that good arguments can be found for both directions of impact. The reduction of the stress level could be due to the increased flexibility, which makes it easier to reduce work-family-conflicts. The flip side of this, however, is what contributes to an increase in the stress level, namely the blurring of the boundaries of working time, an expansion of working hours and the inability to switch off and recover properly. Studies showed that emotional exhaustion increases when working from home [4, 5] and recovery from work may be impaired [6, 7], especially due to the lack of separation between work and personal life. Studies also showed that self-harming behavior and depression increase [8, 9]. Studies also report an increase in musculoskeletal disorders [10–12], possibly due to a poor feasibility of implementing occupational health and safety measures and workplace ergonomics when working from home [13, 14]. This research highlights the importance of maintaining and promoting employees' health when working from home.

As previous research has shown, leaders play an important role in fostering employees' health [15]. Accordingly, scholars have started to develop more health-specific leadership concepts to complement more traditional leadership concepts such as transformational leadership [16], LMX, or consideration. The Health-oriented Leadership (HoL) concept [17] differentiates between health-oriented self-leadership of the leader and employees (SelfCare) and health-oriented employee-directed leadership (StaffCare). SelfCare describes how leaders and employees prioritize their own health, are aware of their health-specific warning signals, and take actions to promote their health. StaffCare encompasses how leaders prioritize their employees' health, are aware of their health-specific warning signals (i.e., signs of overload), and take actions to promote their health.

Leaders have to face leadership-specific hindrances and challenges while leading from home. Contreras and colleagues stated that previous leadership behavior cannot easily be transferred from the traditional workplace to the digital world [18]. For example, trust and communication are important issues [19, 20]. Therefore, it is an open question what happens with Health-oriented Leadership when leading from a distance.

To answer this question, the present study aims to provide an overview of the current research on HoL and, in particular, to shed light on HoL in the digital work context and to identify research gaps. To identify research gaps for HoL in the digital context, we also present previous research of HoL from the traditional work and derive what we do not know yet. In recent years, there has already been a review on healthy leadership by Rudolph and colleagues [21], but their focus was broader and included several concepts of healthy leadership. In the present review, we focus exclusively on HoL. As many recent studies have been published in this area since the last review, it is worthwhile to systematically analyze the current findings on HoL.

The present literature review was conducted as part of the "Digital Leadership and Health" project.

https://doi.org/10.24405/14576

II. HEALTH-ORIENTED LEADERSHIP

A. *Theoretical Concept*

The HoL concept [17, 22] considers health-oriented leadership from three perspectives, namely the health-oriented employee-directed leadership (StaffCare), and the health-oriented self-leadership of leaders and employees themselves (SelfCare). Each SelfCare and StaffCare encompass three sub facets or dimensions: (a) “Value of health” describes how the own (for SelfCare) and employees’ health (for StaffCare) is prioritized; (b) “health awareness” refers to the extent to which own (for SelfCare) and employees’ health-specific warning signals and signs of overload are perceived and recognized (for StaffCare); (c) “health behavior” encompasses specific behaviors actively promoting one’s own (for SelfCare) and employees’ health (for StaffCare) and minimizing health risks (i.e., *improvements in the work environment*, e.g., work organization, ergonomic work environment; and *behavioral prevention activities*, e.g., time management, healthy sitting, taking breaks, balance between private life and work).

B. *Framework and Model Assumptions*

The HoL model assumes that leader SelfCare is positively related to leader health (path a; FIGURE 1). The same applies to employees. Employees high in SelfCare are also supposed to be healthier (path g; FIGURE 1).

Leaders high in SelfCare are also assumed to directly have a positive influence on employee health (path d), but also by encouraging and motivating their employees to take care for their own health (in terms of their own SelfCare) by a role model effect (f; f x g; FIGURE 1). This direct effect of leader SelfCare and employee SelfCare and indirect pathway of leader SelfCare on employee health via employee SelfCare is based on assumptions of the Social Learning Theory [23].

Leader’s own SelfCare does not only promote employee health by encouraging employees’ SelfCare via role model effect but also by facilitating leader’s StaffCare (path b x c; consistent behavior). Leaders high in SelfCare are assumed to be more able to take care for their employees’ health in terms of StaffCare (path b; FIGURE 1). In turn, leader’s StaffCare directly positively influences employee health (path c) by giving high priority to their followers’ health (“value of health”), by paying attention to their warning signals and signs of overload at an early stage (“health awareness”), and by demonstrating specific health-promoting actions (“behavior”; e.g., providing healthy working conditions and appropriate resources [e.g., positive climate, work design], addressing health issues, motivating followers to adopt health-promoting behavior [e.g., avoid presentism, avoid excessive overtime, etc.]). StaffCare does not only directly influence employee health but also indirectly by encouraging employees to take care for their own health via employee SelfCare (path e and e x g; FIGURE 1). Furthermore, leaders taking care for their employees’ health are also assumed to feel better and healthier themselves (path i; FIGURE 1).

Another central assumption of the HoL is the crossover effect between leader health and employee health (path h; FIGURE 1). Leaders who are strained are more likely to transfer their own pressure to their employees leading to a lower employee health. FIGURE 1 shows the core assumptions of the HoL model and modifications drawn from the state of the current research.

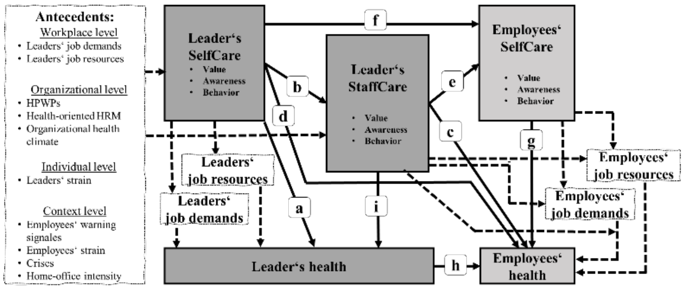


FIGURE 1: HEALTH-ORIENTED LEADERSHIP CONCEPT AND ADAPTED FRAMEWORK MODEL.

III. LEADING FROM THE DISTANCE

For example, **trust** in employees is a key challenge for leaders when leading from the distance [19]. Leaders may be concerned that some employees are busy with private matters at home and less engage in their work tasks. Since they are not aware of how much their employees really work, they may assume that their employees are less committed and less productive when working from home [19]. Insufficient trust often leads to leaders starting to control their employees with frequent calls and attendance checks when working from home. This, in turn, leads to dissatisfaction and demotivation among employees. They do not only feel restricted in their autonomy and scope of action, but also the worry that one's leader does not trust one is experienced as frustrating [19, 24]. Concerns about not being able to adequately control productivity and commitment is a major issue for leaders [19].

While working from home, communication changes from mostly face-to-face to digital communication via mail, videocalls, or phone. When digitally communicating, leaders may face more communication obstacles, as fewer physical and visual cues are available, these cues may be more easily overlooked, less information is transmitted, and responses (feedback) are delayed [25, 26]. The lack of nonverbal cues in digital communication leads to a reduced transmission of all necessary information [27]. The limited flow of information and fewer non-verbal cues during digital communication may make it more **difficult** for leaders **to perceive and interpret employees’ moods and feelings**, to **recognize signs of overload**, and to take adequate countermeasures [28]. Thus, it may be not only challenging to motivate employees sufficiently to perform well when working from home, but also to pay attention to employees' health from a distance.

In addition, limited communication channels can lead to increased **misunderstandings** [20, 29]. As a leader, it is not always easy to identify conflicts early on and take effective action when working from home. While leaders in the office quickly get a sense of a bad mood and potential conflicts, this may remain undetected when leading from the distance [29, 30]. Therefore, leaders may detect conflicts too late, and the conflicts may have already escalated. It is also more difficult to understand all conflict parties as well as the problem in its entirety and to deal with it in a way that everyone is satisfied with a solution.

Studies have shown that communication and regular contact and encounters between leaders and employees decrease while work from home [31]. Moreover, informal and relationship-promoting communication is more difficult when working from home [32]. This can further lead to a lower relationship quality and reduced personal connectedness [33]. Overall, effective communication via digital media is more difficult [34].

Since it is to be expected that employees also continue working from home after the Covid-19 pandemic and given the need to promote occupational health when working from home, it is particularly important to understand how Health-oriented Leadership can be transferred to the digital context and if it is also effective here. The presented leadership-specific challenges and hindrances might make it difficult for leaders to adjust their employees' work assignments, balance their employees' demands and resources, and thus lead in a way that promotes health and performance [28, 35].

IV. Methods

For this literature review, relevant databases were searched for relevant publications. On the one hand, published peer-reviewed scientific studies were included, including quantitative studies and experiments, qualitative studies, reviews, and meta-analyses. On the other hand, reports and recommendations for action, many of which were published in response to the pandemic, were also reviewed. In addition, references to relevant literature in the publications were followed up and we were also made aware of further relevant publications by experts in the course of the literature search.

In this literature review, we follow the understanding of working from home according to Lal and Dwivedi [36] (p. 257): "Homeworking" which involves individuals undertaking traditionally office-based paid employment from home by means of information and communications technologies (ICTs) on a full- or part-time basis." We are referring here to the performance of work that was previously performed primarily on the employer's premises, from home or another location, using IT, as a member of a fixed team and with colleagues who perform their work either from the shared company location or from home. In English, the terms telework, telecommuting, or working from home are often used for this [37].

V. Results: Current State of Research

A. *Distinctiveness and Incremental Validity*

Franke and colleagues [17] were able to show a positive effect of StaffCare on employee health that went beyond the influence of transformational leadership. The incremental validity of HoL beyond the effects of transformational leadership was also confirmed in other studies [38–40].

B. *Direct Effects and Effectiveness*

1) *SelfCare*

Regarding *health-related outcomes*, previous studies showed that SelfCare is positively related to general health [17, 22, 41, 42], well-being [43], and negatively associated with irritation/ strain [17, 22, 41, 42], health complaints [17, 22, 41–43], burnout/exhaustion [38, 43–47], depression [43], presentism [22], and work-family conflict [17, 22]. Regarding *work-related attitudes,* studies showed that SelfCare is positively related to work engagement [45, 46] (path a and g; Figure 1).

These studies refer to the traditional work context, but so far little is known about SelfCare in the digital work context. There have been only scattered studies examining health-oriented self-leadership in terms of SelfCare in the home-office context. Initial findings from an interview study by Efimov et al. [48] show that virtual leaders place a high value on their own health and show a high level of attentiveness to their own warning signals. In particular, physical activity and setting boundaries (boundary management) were mentioned as health-oriented self-leadership behaviors. A diary study by Müller and Niessen [49] focused on general self-leadership, not specifically on health-oriented self-leadership, but important conclusions can be drawn here as well. The authors were able to show that employees on home-office days reported higher self-goal setting, higher self-reward, and higher visualization of successful performance than on office days. The effects of work location on these self-leading behaviors were thereby mediated by experienced autonomy. In addition, there was a direct effect of work location on ego depletion and job satisfaction. Employees who work only partially from home were less exhausted and more satisfied with their work on home-office days than on office days. The authors concluded that working from home allows for more flexibility, e.g., in terms of workplace design, task scheduling, prioritization and selection of tasks, but that this requires the appropriate self-leading skills.

However, it is unclear how well health-oriented self-leadership in terms of SelfCare succeeds when working from home and how effective it is compared to the traditional work context. So far, only one qualitative study to date has focused on health-oriented self-leadership in the digital work context. Since working from home has both opportunities and risks for health, future empirical research on health-oriented self-leadership in the digital context is required for a better understanding.

Regarding *the effects of leaders' SelfCare on employees' health* (path d; Figure 1), Pundt and Felfe showed a negative relationship between leaders' health-endangering SelfCare behavior and employees' health, and a positive relationship with employees' health complaints and presentism [22]. Klug and colleagues also showed a positive relationship between leaders' SelfCare and employee health, and a negative relationship to employee strain and health complaints [41]. In line with these findings, Grimm and colleagues considered both leader and employee level and found a positive relationship between leader SelfCare and employees' engagement and a negative relation to employees' exhaustion [45]. However, another study considering both leader and employee level did not find an effect of leaders' SelfCare "awareness" on employees' exhaustion and cynicism, but for the sub facet "behavior". They found a cross level effect on employees' exhaustion in one of their two examined organizations [50]. A another multilevel study by Klug and colleagues did also not show an effect of leader SelfCare on employee health, strain, and health complaints [42]. However, they found that leader SelfCare indirectly affects employee health via StaffCare.

Regarding the effects of leader SelfCare on employee health, the findings are somewhat inconsistent. Therefore, further studies are needed to systematically investigate the underlying effects here in more detail. In particular, in a digital context, leader SelfCare may be barely visible to employees. It is conceivable that the effects are weakened due to the lack of direct contact and opportunities to perceive the leader's SelfCare.

2) StaffCare

Regarding effects of *employees' health-related outcomes*, several studies show that *StaffCare* is positively related to employee general health [17, 22, 41, 42, 51–53], mental health [54], well-being [43] and negatively related to employees' physical and psychosomatic health complaints [17, 22, 41–43, 51, 53, 55, 56], strain [17, 22, 41, 42, 51, 53], burnout/exhaustion [22, 38, 43–47, 57–59], depression [43, 60], anxiety [60], presentism [22], and work-family conflict [17, 22]. Regarding *work-related attitudes*, studies also show that StaffCare is positively related to employees' work engagement [38, 45, 46, 51, 59], job satisfaction [22, 53], task proficiency [58], and commitment [51, 52, 55] (path c; FIGURE 1).

Moreover, studies show that StaffCare fosters employees' disclosure intentions to leaders [39] and is positively related to employees' intention to participate in occupational health promotion activities, and actual participation [61].

Regarding multilevel effects of leader StaffCare on employee health, Grimm and colleagues showed that StaffCare was marginally positively related to individual employee engagement and exhaustion [45]. Vonderlin and colleagues examined how leader and employee ratings of Health-oriented Leadership in terms of StaffCare correspond to each other and which sources are predictive for employee mental health [60]. They showed that leaders' self-ratings of StaffCare were related to their employees' ratings (at the team level) on the "behavior" dimension, but not on the "awareness" and "value of health" sub facets. Also, leaders rated themselves significantly higher on StaffCare compared to their employees. Employee ratings of StaffCare significantly predicted their own level of mental distress (direct within-level effect), whereas leaders' ratings of StaffCare did not predict employees' mental distress at the team level (direct cross-level effect). Leaders' self-ratings of StaffCare did not influence the relationship between employee ratings of StaffCare and their mental distress on an individual level (cross-level interaction).

Regarding *effects of leaders StaffCare on their own health* (path i; FIGURE 1), Pundt and Felfe showed positive relationships between StaffCare "awareness" and leaders' general health and negative relationships with leaders' strain, and work-family conflicts [22]. The "behavior" facet showed positive associations with leaders' health state and a negative relation to work-family conflicts [22]. Additionally, Grimm and colleagues found that leaders' StaffCare positively relates to their own work engagement and negatively to their own exhaustion [45].

There are also studies examining *conditions for the effectiveness of StaffCare*. For example, a study by Klebe and colleagues [58] showed that StaffCare is particularly important for employees' health in times of crisis: StaffCare has a particularly positive influence on employees' health when their health is threatened by a crisis situation. Particularly when employees are dependent on the support of their leader, health-oriented leaders can have a positive influence on employee health and make an important difference to their mental health. Another study by Klebe and colleagues showed that StaffCare was more effective for follower health the stronger the crisis was. The results were largely supported in a subsample when exhaustion was measured 1 week later [47]. Findings underline that StaffCare was jeopardized but gained in importance during the pandemic. By displaying StaffCare, leaders can buffer negative crisis effects on followers.

Overall, StaffCare thus has a positive influence on the health and other work-related attitudes of employees in a traditional work setting. However, little is known about the effects of StaffCare in a digital work context. We are only aware of two studies. In an interview study with 13 leaders of virtual teams Efimov and colleagues [48] showed that leaders also attach great importance to Health-oriented Leadership in virtual collaboration. They considered communication, trust-building, support in drawing boundaries between work and private life (work-life boundary management), and face-to-face meetings to be the most important leadership behaviors. Support from the organization is also seen as particularly relevant by the leaders.

Following up on these findings, Klebe et al. [62] examined the effectiveness of StaffCare in the home-office. Using a sample that worked exclusively from home, the authors were able to show that StaffCare is also positively associated with employees' health and commitment in the digital context. However, this study also showed that the effectiveness of StaffCare in the digital context can be subject to limitations: If employees working from home have to deal with a high level of technical disruptions (e.g., computer crashes, poor audio and video quality), the positive influence of StaffCare on employees is reduced. Organizations should ensure a reliable IT infrastructure so as not to jeopardize leadership effectiveness and thus employee health.

Overall, the evidence base on HoL in terms of StaffCare in the digital context is still limited. Apart from an interview study and one empirical study, there is still a lack of research that provides information on the potential of both SelfCare and StaffCare in a digital context. Since StaffCare has an important influence on employees' well-being, future studies should investigate further opportunities and risks for both SelfCare and StaffCare in the digital context.

C. Indirect Mechanisms

1) Indirect Effects of StaffCare via Employee SelfCare

Studies also showed evidence for the postulated *indirect effect of StaffCare on employees' health via employee SelfCare* (path e x g; FIGURE 1) [17, 38, 43, 44, 47, 63]. This means that leaders' StaffCare leads to improved employees' SelfCare, which in turn contributes to better health and a better work-life balance among employees. For example, Kaluza and colleagues showed that employees' SelfCare mediated the association between StaffCare behavior and exhaustion [38]. Another study confirmed this indirect effect and showed that StaffCare at T1 positively relates to employee SelfCare at Time 2, which is negatively associated with employee exhaustion at Time 3 [63].

The study by Klebe and colleagues [47] on StaffCare in crisis situations was also able to confirm this indirect effect: 1) a crisis situation leads to a lower level of StaffCare. 2) Since leaders show less consideration for their employees' health, employees themselves have less capacity to protect their own health in terms of SelfCare. 3) If employees show less SelfCare, this is also reflected in poorer mental health.

Regarding the digital work contexts, it is yet unclear if the indirect effect of StaffCare via employee SelfCare still remains, as leaders might not be successful in transferring their StaffCare via digital communication. More research is needed which role the digital work context plays for this indirect effect.

2) Indirect Effects of StaffCare and SelfCare via Work Conditions

Regarding *other indirect effects of StaffCare*, a study by Grimm et al. [45] was able to show that the effects of StaffCare on employee engagement are mediated through team resources such as role clarity, support from the leader and colleagues, or professional development opportunities. They further showed that the relationship between leader StaffCare and employee exhaustion was mediated by employee job demands. Horstmann and Remdisch [55] also showed that StaffCare promotes employess' resources and minimizes job demands and thus has an indirect effect on employees' health and commitment. Kaluza and Juncker showed that StaffCare at T1 indirectly affects employee exhaustion at T3 via perceived team health climate at T2 [63].

Regarding the *indirect effect of SelfCare via resources and job demands*, Grimm and colleagues showed a significant indirect effect for leader SelfCare on leader engagement through leader job resources, and for leader SelfCare on leader exhaustion through leader job demands [45].

There are also studies that did not exactly examined the mediation effects but showed a positive link between employees' SelfCare [22], leaders' SelfCare [64], and StaffCare [22] on the one hand to employees' job demands and resources on the other hand.

So far, nothing is known about the indirect effects of HoL in the digital context and whether leaders high in StaffCare are able to influence their employees' job demands and resources and indirectly positively influences their health when working from home. Regarding the digital work context, it would further be interesting to examine whether and how SelfCare indirectly influences employees' and leaders' health via influencing job resources and job demands at the home-office. Moreover, a potential interaction between SelfCare as a resource and other resources in terms of a positive resource gain spiral according to the COR theory [65] would be worth examining in the digital context to provide further evidence for the role of SelfCare as an important resource in the digital work context. Based on the JD-R model, it is also conceivable that SelfCare helps to buffer against the negative influences of job demands and job stressors.

3) Indirect Effects of Leader SelfCare via StaffCare and Employee SelfCare

Drawing on the COR theory and the HoL concept, a multilevel study by Klug and colleagues [42] tested two mechanisms through which employees may benefit from self-caring leaders: (a) *through StaffCare*, that is, concern for their employees' health (improved leadership hypothesis; path b x c (FIGURE 1); and (b) through a direct relationship between leaders' and employees' SelfCare (role-modeling hypothesis). Their findings revealed that leader SelfCare was positively related to leader-rated StaffCare at Level 2, which was positively related to employee-rated StaffCare at Level 1. In turn, employee-rated StaffCare was positively related to employee health. They provide evidence for the indirect effect of leader SelfCare on employee health via leader StaffCare and employee-rated StaffCare for strain and overall health. The findings support the improved leadership hypothesis and underline the importance of leader SelfCare as a determinant of StaffCare. This indirect effect is also confirmed by Arnold and Rigotti [46].

Regarding the *role model effect of leader SelfCare on employee SelfCare* (path f; FIGURE 1), there are only a few studies yet. Klug and colleagues found a positive relationship between leaders' SelfCare and employees' SelfCare [41]. The aforementioned multilevel study by Klug and colleagues [42] did not find an effect of leader SelfCare on employee SelfCare. They also did not find indirect effects of leader SelfCare on employee health via employee SelfCare (path f x g; FIGURE 1).

More research is needed to examine the role model effect. Especially in the digital work context, it is not clear if employees are able to perceive role model behavior of their leaders at all when working at home. The limited visibility of leaders' SelfCare for employees might diminish a potential role model effect when working from home.

4) Buffering effect of StaffCare

Based on assumptions of the JD-R model, studies have examined the buffering effect of StaffCare on the relationship between employees' job demands and their health (e.g., strain, burnout) and job satisfaction [53, 57]. Santa Maria and colleagues showed that StaffCare "awareness" and "value" buffered the effects of work effort on police officers' burnout levels [57]. Krick and colleagues showed that employees with a leader high in StaffCare are less likely to experience strong negative effects on their health and job satisfaction when facing high job demands and work stressors [53]. These studies have shown that StaffCare can be seen as an essential work resource that counteracts negative effects of high work stress.

It is conceivable that StaffCare could also be an effective resource in the digital context with regard to home-office and ICT-specific stressors. On the other hand, it is conceivable that StaffCare would have no effect here, since StaffCare could lose effectiveness due to the limited transmission of information during digital communication.

Bregenzer and Jimenez [66] investigated this question in a survey study. The authors were able to show that a lack of technical support in the digital work environment leads to an increase in stress among employees. However, health-promoting leadership can mitigate these effects: If leaders show health-promoting leadership when technical support is inadequate, the stress level among employees is lower than when little or no StaffCare is shown. However, negative effects of other risk factors in the digital work context (e.g., constant availability) could not be mitigated by health-promoting leadership in this study.

So far, there is only one empirical study on the buffering effect of StaffCare in the digital context. The question of whether StaffCare can also mitigate negative effects of job demands and ICT stressors in the digital context therefore remains largely unanswered. Future studies should therefore investigate the potential buffering effect of StaffCare with regard to other risk factors in the digital work context.

D. Crossover Effects

Based on the assumption that strain could transfer between leaders and followers through social exchange [67], specifically when leaders and employees work closely together, the HoL model further assumes that the leaders' own health state also has an influence on employees' health state (path h; FIGURE 1). In the literature this effect is called crossover effect. Köppe and colleagues [56] did not find a direct crossover effect of leaders' exhaustion on employees' somatic complaints in the traditional work context, but they found an indirect effect mediated by leaders' StaffCare, such that leader health was related to StaffCare which in turn was related to follower health. Wirtz and colleagues examined the crossover effect from employees to the leader and found that employees' work engagement leads to leaders' work engagement, but employees' emotional exhaustion was not directly related to leaders' emotional exhaustion over time [68]. Future research is therefore needed to further investigate and provide more insight into crossover effects in both directions. It is not yet known whether a crossover effect can occur when leaders and employees communicate exclusively digitally. Therefore, further research is needed to examine the crossover effect in the digital work context.

E. Antecedents of HoL

As a better understanding of favorable and hindering factors of HoL may help organizations to improve their occupational health promotion and psychosocial risk management, it seems important to understand which antecedents facilitate or hinder HoL [46, 58].

Workplace level: Based on the established Job Demands-Resources Model [69] differentiating between *demands and resources* to explain work experience and behavior and the Conservation of Resources Theory [70], several studies examined antecedents of HoL.

A study by Arnold and Rigotti [46] showed that job resources are positively and job demands are negatively related to leader SelfCare. Leader SelfCare in turn leads to more StaffCare, which in turn leads to more work engagement among employees. They also found positive relationships between job resources and StaffCare and negative relationships between job demands and StaffCare. These results indicate that leaders experiencing more job resources and less job demands overall, show more SelfCare and StaffCare. These findings were confirmed by another study by Krick and colleagues [71]. Work-related resources such as *social support and autonomy* are conducive conditions and enable SelfCare and StaffCare, whereas work demands such as *multitasking and permanent availability* are hindering factors. These studies showed that leaders' resources and demands represent important antecedents for SelfCare and StaffCare. Pischel and colleagues used an experimental study and a survey study to examine antecedents (a) clarity of displayed warning signals in followers, b) leaders' stressors, c) *leaders' autonomy*) of StaffCare "awareness" in followers and leaders [72]. They show that leaders had a lower StaffCare "awareness" during times of low autonomy.

Organizational level: A study also considered organizational factors such as *High-Performance Work Practices (HPWPs)* and *health-oriented human resource management strategies* as antecedents facilitating SelfCare and StaffCare. They found a positive relationship between HPWPs and HoL. They also showed that HRM practices related to employee health show a positive relationship with HoL indicating that a general climate or culture of concern for employees' and leaders' health can provide a resource for leaders that helps them to engage in HoL [71]. A study by Kaluza and colleagues investigated *organizational health climate* as an antecedent of StaffCare "awareness" and StaffCare "behavior" [59]. They showed that leaders' perceptions of organizational health climate were positively related to their health mindsets (i.e., their health awareness) and in turn was positively associated with their health-promoting leadership behavior, which ultimately went along with better employee well-being.

Individual level: Studies also examined *leaders' own strain* as an antecedent of HoL and showed that leaders' own stress level makes it more difficult for leaders to lead themselves and their employees in a healthy way [73, 74]. Leaders who are exhausted show less SelfCare behavior, as a study by Köppe and Schütz [74] showed. Another study by Köppe and colleagues [56] also showed that leaders' exhaustion is negatively associated with leaders' StaffCare. An experimental study by Klebe and colleagues [73] showed that it is more difficult for leaders to lead in a health-promoting manner when under stress. The aforementioned study by Pischel and colleagues focused on antecedents of StaffCare "awareness" and also showed that leaders had a lower awareness during times of high stress [72].

Context level: The aforementioned experimental study by Klebe and colleagues [73] also showed that it is more difficult for leaders to lead in a health-promoting manner in critical situations. When leaders have to counteract a *crisis situation*, StaffCare decreases due to a lack of resources and capacities on the part of the leaders. It is particularly challenging for leaders to show StaffCare when they experience strain in a critical situation. In addition, they investigated the influence of *employees' stress level* as a contextual influence factor on StaffCare. Here, a positive effect on StaffCare was revealed: Leaders in turn make more of an effort to lead in a way that promotes health when they perceive that their employees are under great psychological strain. Although leaders show less StaffCare in critical situations and when they experience high psychological strain, they show more StaffCare when they notice that their employees are stressed.

The experimental study by Pischel and colleagues examined *clarity of displayed warning signals* in followers as an antecedents of StaffCare "awareness" [72]. Their results showed that leaders are less able perceive warning signals and signs of overload in their employees when followers displayed less clear warning signals.

The fact that StaffCare decreases in critical situations was also confirmed in another study by Klebe and colleagues in the context of the Corona pandemic [47]. They showed that crisis severity is indirectly related to exhaustion via StaffCare and SelfCare: 1) crisis severity is related to leader StaffCare, 2) which is related to follower SelfCare and 3) in turn with exhaustion.

The aforementioned study by Krick and colleagues also examined leaders' **home-office intensity** as a predictor of leaders' SelfCare and StaffCare [71]. They showed that working from home seems to favor SelfCare and StaffCare and thus represents a supportive condition of HoL. Possibly, higher flexibility and better work-life-balance offer more opportunities for SelfCare and StaffCare when working from home. Moreover, it is possible that leaders feel more responsible for their employees' health due to a lack of direct contact. However, it may be more difficult to act from the distance. Future research should identify the relevant reasons and mechanisms.

Future studies should also examine home-office specific resources and job demands of leaders as antecedents of leaders' SelfCare and StaffCare. Certainly, previous relationships between job demands, resources from the traditional work context and HoL can also be transferred to the digital context, but it is unclear whether, for example, home-office specific or ICT-specific stressors also influence StaffCare and SelfCare. It is conceivable that work-related stressors of leaders in the home-office can have a negative impact on employee health via a decrease in StaffCare and employee SelfCare. On the other hand, it is also conceivable that work-related and home-office specific resources of leaders can positively influence employee health through an increase in StaffCare and SelfCare. Which home-office specific resources and job demands directly influence leaders' StaffCare and SelfCare and indirectly employees' health should be investigated in future research. This is an important starting point for future research.

F. *Profiles of HoL*

Most studies show a positive correlation between leader SelfCare and StaffCare [22, 42, 45, 46] (path b; FIGURE 1) as well as between StaffCare and employee SelfCare [17, 22, 38, 41–44] (path e; FIGURE 1).

Although relationships are often moderate to high, they are not perfect, and SelfCare and StaffCare do not always go hand in hand but can also be pronounced differently. A study by Klug and colleagues [41] therefore investigated the extent to which different constellations of HoL can be observed and how they are related to employee health. In their study, a total of four different profiles of HoL could be empirically identified and confirmed: A consistent positive profile (high care), a consistent negative profile (low care), as well as two inconsistent profiles with regard to employee SelfCare, leader SelfCare, and StaffCare (leader sacrifice and follower sacrifice). Employees in the high care profile, characterized by consistently high SelfCare and StaffCare, reported the highest health scores compared to the low care and the two inconsistent profiles. The follower sacrifice profile, characterized by higher SelfCare of the leader compared to StaffCare of the employee, showed higher psychological stress among employees than the leader sacrifice profile (characterized by higher StaffCare of the employee, but comparatively low SelfCare of the leader). As expected, psychological stress was highest among employees in the so-called low care profile, which was characterized by consistently low levels of StaffCare and SelfCare. The results show that not only consistently negative leadership behavior can worsen employee health, but that even inconsistent behavior with regard to StaffCare and SelfCare can impair the mental health of employees.

So far, it is not known whether these profiles of HoL can be found exclusively in the traditional work context with a lot of face-to-face contact, or whether these profiles are also evident in the digital work context. It would also be interesting to know whether the different profiles of HoL have the same impact on employees when they work from home, or whether their effect decreases or perhaps even increases in the digital context. It is conceivable that some leaders might succeed in showing StaffCare and at the same time motivate their employees to take care for their own health (in terms of SelfCare) because they communicate sufficiently and use digital media effectively. It might also be possible that leaders find ways to be a good role model by openly talking about their health behavior and how they stay healthy when working from home. However, due to the specific working conditions when working from home (e.g., digital communication through ICT), the visibility of leaders' StaffCare and SelfCare could be limited when leading from a distance. Leaders may have difficulties conveying StaffCare and being a role model through digital media. It would be possible that not only the limited visibility of leaders' health-oriented (self-)leadership behavior, but also the own experienced risks at the home-office, lead to a rather opposing relationship between StaffCare, leaders' SelfCare, and the SelfCare of the employees. However, independent employees whose health has a high priority for them, could still succeed in taking good care of themselves. It would also be conceivable that employees focus on their own health even more because no one else does. This would rather lead to an inconsistent profile.

An investigation of this issue is currently pending. Furthermore, nothing is yet known about antecedents of these different profiles and differences regarding performance, engagement or commitment.

G. *Interventions of HoL*

To promote Health-oriented Leadership, researchers and practitioners have developed leadership intervention, for example the HoL process (an intervention on the team level), the GoFüGo training (an intervention to promote Health-oriented Leadership competences), and the Mindfulness- and Skill-Based Health-Promoting Leadership Intervention [75–77]. The GoFüKo training is a one-day workshop for leaders and can serve as a preparation for a following HoL process with the leader and the team. The training aims to achieve three goals: 1) to provide knowledge and facts about Health-oriented Leadership, occupational health management and the significance for health, 2) to help leaders to reflect on their own strengths and potential regarding their SelfCare and StaffCare, and 3) to improve SelfCare and StaffCare by exercises, action plans, and exchange among participating leaders. The workshop consists of four parts: (1) Warm up (introduction, getting to know each other, facts on HoL, OHM, etc.), (2) SelfCare, (3) StaffCare, and (4) Cool down (including transfer of what has been learned into everyday working life). Both the SelfCare and StaffCare part contain self-reflection and exercises addressing the sub dimensions "value", "awareness", and "behavior" [75].

The HoL process aims to identify all relevant characteristics of Health-oriented Leadership as a status quo assessment for a leader and the team. In a feedback process, leader and team become aware of strengths and weaknesses regarding SelfCare and StaffCare and develop measures for a better health promotion in their workplace. This process consists of nine systematic steps: (1) coordination with management, (2) information event on HoL for the leaders, (3) preliminary talk with the leader, (4) kickoff event with the team and the leader, (5) participation in online survey (HoL instrument; team and leader), (6) evaluation and preparation of the HoL report (leader), (7) coaching with the leader, (8) evaluation workshop for the team with the leader, (9) follow-up workshop after approximately 3 months (team and leader). The process is professionally guided and moderated by a coach [40, 75, 77, 78].

The Mindfulness- and Skill-Based Health-Promoting Leadership Intervention consists of three full-day courses (8 hr each) and two 3-hour booster sessions with a total training time of 30 hours over a period of 6 months containing three modules: (a) SelfCare, (b) StaffCare, and (c) addressing employees under stress. The intervention includes information transfers, demonstrating their scientific backgrounds and emphasizing the importance of each topic, mindfulness practices, practical everyday skills to foster behavioral change [76].

There are several studies that have examined the effectiveness of interventions to promote HoL. Stuber and colleagues [79] examined the effectiveness of HoL interventions in a systematic review. They demonstrated that 4 of the 7 included studies showed a significant improvement in employee mental health as a result of the leadership interventions. None of the eligible studies showed a negative effect on employee mental health. Two studies showed no effect. They concluded that leadership interventions with reflective and interactive parts in group settings over several seminar days appear to be the most promising strategy for promoting mental health among healthcare workers. Another systematic review by Dannheim and colleagues [80] also showed significant effects of leadership training on employees' exhaustion, self-reported sickness absence, work-related sickness absence and job satisfaction when comparing health-oriented leadership interventions to no intervention. For studies comparing health-oriented leadership training to other training they found no significant effects. Vonderlin and colleagues [76] developed the mindfulness- and skill-based HoL intervention and investigated its effectiveness in a quasi-experimental multisite field study including supervisor and employee ratings from 12 German companies. They compared their intervention group to a passive control cohort based on propensity score matching. Their results showed that the supervisors who had participated in the HoL intervention experienced a significantly larger decrease in mental distress and an increase in SelfCare as well as StaffCare than did their matched controls. They also showed that the effect on supervisors' mental distress was mediated by an increase of their SelfCare and moderated by the frequency of their mindfulness practice. However, they did not find significant effects between groups regarding employee level outcomes. Evaluations of the HoL process revealed that leaders and team members were quite satisfied with the improvement in SelfCare and StaffCare, and that most agreements were implemented after three months [78].

As the empirical evidence of the effectiveness of HoL interventions for supervisors and their employees is still scarce, more effort to develop and evaluate such interventions is needed. Furthermore, these interventions were designed to promote health-oriented leadership in traditional work settings. Since health-oriented leadership (in terms of StaffCare) and health-oriented self-leadership (in terms of SelfCare) represent important competencies when working from home, interventions to promote these competencies should be developed. In this context, it is particularly important to consider possible challenges in the digital work context for SelfCare and StaffCare. Further studies should examine their effectiveness to promote employees' and leaders' health when working from home.

H. Methodology of previous research

Most of the previous studies have a cross-sectional design [43, 44, 52, 55, 74]. However, there are also studies that collected their data at least at two different time points to reduce biases such as the common method bias [17, 22, 38, 47, 51, 54, 56, 62, 63, 71]. There are also several studies that collected matched data considering both perspectives of leaders and employees [41, 42, 45, 50, 56, 59, 60]. These studies were thus able to conduct multilevel analyses [42, 45, 60] considering the leaders' level and team level. Furthermore, besides the common variable-centered approach, one study focused on a person-centered approach and examined profiles of HoL [41]. More current studies also examined antecedents and effectiveness of HoL using experimental designs to shed more light on causality [38, 58, 62, 72, 73]. Overall, the research to date shows a wide range of diverse methodological approaches to investigate effects of HoL.

VI. CONCLUSION

Overall, the current evidence confirms that the concept of Health-oriented Leadership is a valid construct that can have a positive influence on employee health beyond other leadership styles [17, 38]. Health-oriented Leadership can have a positive impact not only on employee health, but also on other work-related attitudes such as job satisfaction, commitment, or performance [22, 53, 58]. While previous studies were mostly conducted pre-pandemically in a traditional work context with regular face-to-face contact, there have been only a few studies to date on Health-oriented Leadership in the digital context. Initial empirical findings indicate that the effectiveness of Health-oriented Leadership in the digital context may be limited by technical problems. From these initial findings and based on previous research on leadership in times of crisis [58, 73], a **first research perspective** for future research can be derived. As shown in FIGURE 2, future research should take a closer look at the extent to which the effectiveness of StaffCare and SelfCare might be reduced (i.e., moderated) by home-office specific demands such as technical problems or permanent availability or home-office intensity itself, or even increased by resources such as higher flexibility.

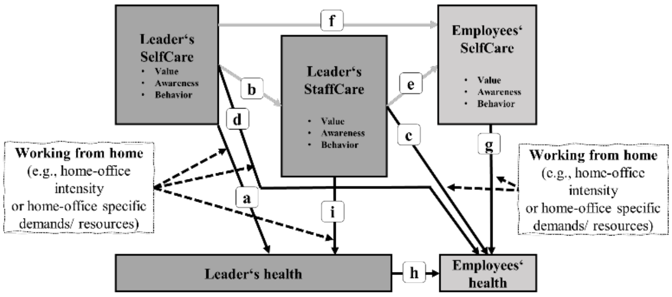


FIGURE 2: RESEARCH PERSPECTIVE I FOR HOL IN A DIGITAL WORK SETTING: EFFECTIVENESS OF HOL AND THE MODERATING ROLE OF HOME-OFFICE SPECIFIC WORK CHARACTERISTICS.

There are already initial findings that HoL is also of importance in the digital work context, since StaffCare can positively influence the health and commitment of employees even when working from home and mitigate the negative effects of inadequate technical support. This highlights a **second research perspective** of HoL in the digital context. Future research could further shed light on mechanisms of HoL in the digital work context. One potential mechanism might be the buffering effect of StaffCare. It is an open question, if leaders high in StaffCare are able to buffer against the negative effects of employees' home-office specific or ICT demands (e.g., technical problems, constant availability) on their health. A second mechanism could be indirect effects of SelfCare and StaffCare mediated through home-office specific demands and resources. Both potential mechanisms (both moderating and mediating effects) are displayed in FIGURE 3.

The perspectives presented could provide a valuable starting point for future studies.

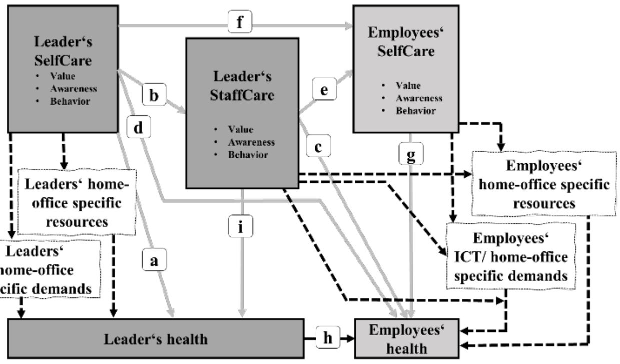


FIGURE 3: RESEARCH PERSPECTIVE II FOR HOL IN A DIGITAL WORK SETTING: INDIRECT AND MODERATING EFFECTS OF HOL.

ACKNOLODGEMENT

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project Digital Leadership and Health].

REFERENCES

[1] M. Diewald, “Zukunftsperspektiven von Homeoffice nach Corona,” in *Sonderband Zukunft der Arbeit, HR Consulting Review*, J. Nachtwei and A. Sureth, Eds.: VQP, 2020, pp. 30–33.

[2] DAK, *Digitalisierung und Homeoffice in der Corona-Krise: Update: Sonderanalyse zur Situation in der Arbeitswelt vor und während der Pandemie.* [Online]. Available: https://www.dak.de/dak/download/studie-pdf-2448800.pdf (accessed: Jul. 29 2022).

[3] A. I. Tavares, “Telework and health effects review,” *International Journal of Healthcare*, vol. 3, no. 2, p. 30, 2017, doi: 10.5430/IJH.V3N2P30.

[4] S. Chong, Y. Huang, and C.-H. D. Chang, “Supporting interdependent telework employees: A moderated-mediation model linking daily COVID-19 task setbacks to next-day work withdrawal,” *Journal of Applied Psychology*, vol. 105, no. 12, pp. 1408–1422, 2020, doi: 10.1037/apl0000843.

[5] S. R. Sardeshmukh, D. Sharma, and T. D. Golden, “Impact of telework on exhaustion and job engagement: a job demands and job resources model,” *New Technology, Work and Employment*, vol. 27, no. 3, pp. 193–207, 2012, doi: 10.1111/J.1468-005X.2012.00284.X.

[6] A. M. Wöhrmann, N. Backhaus, A. Tisch, and A. Michel, *BAuA-Arbeitszeitbefragung: Pendeln, Telearbeit, Dienstreisen, wechselnde und mobile Arbeitsorte: Forschung Projekt F 2452,* 1st ed. Dortmund, Berlin, Dresden: Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA), 2020.

[7] N. Backhaus, A. M. Wöhrmann, and A. Tisch, *BAuA-Arbeitszeitbefragung: Telearbeit in Deutschland.* [Online]. Available: https://www.baua.de/DE/Angebote/Publikationen/Bericht-kompakt/Telearbeit.pdf?__blob=publicationFile&v=4

[8] W. Campione, “Employed Women’s Well-Being: The Global and Daily Impact of Work,” *Journal of Family and Economic Issues*, vol. 29, no. 3, pp. 346–361, 2008, doi: 10.1007/s10834-008-9107-x.

[9] Y. Lott, “Work-Life Balance im Homeoffice: Was kann der Betrieb tun?,” *WSI Report*, vol. 54, 2020. [Online]. Available: https://www.boeckler.de/pdf/p_wsi_report_54_2020.pdf

[10] Eurofound, *Living, working and COVID-19, COVID-19 series*. Luxembourg: Publications Office of the European Union, 2020.

[11] S. Montreuil and K. Lippel, “Telework and occupational health: a Quebec empirical study and regulatory implications,” *Safety Science*, vol. 41, no. 4, pp. 339–358, 2003, doi: 10.1016/S0925-7535(02)00042-5.

[12] J. L. O. Beckel and G. G. Fisher, “Telework and Worker Health and Well-Being: A Review and Recommendations for Research and Practice,” *International Journal of Environmental Research and Public Health*, vol. 19, no. 7, 2022, doi: 10.3390/ijerph19073879.

[13] M. Bretschneider-Hagemes, “Belastungen und Beanspruchen bei mobiler IT-gestützte Arbeit — Eine empirische Studie im Bereich mobiler, technischer Dienstleistungen,” *Zeitschrift für Arbeitswissenschaft*, vol. 65, no. 3, pp. 223–233, 2011, doi: 10.1007/BF03373840.

[14] J. O. Crawford, L. MacCalman, and C. A. Jackson, “The health and well-being of remote and mobile workers,” *Occupational Medicine*, vol. 61, no. 6, pp. 385–394, 2011, doi: 10.1093/occmed/kqr071.

[15] D. Montano, A. Reeske, F. Franke, and J. Hüffmeier, “Leadership, followers' mental health and job performance in organizations: A comprehensive meta-analysis from an occupational health perspective,” *Journal of Organizational Behavior*, vol. 38, no. 3, pp. 327–350, 2017, doi: 10.1002/job.2124.

[16] B. M. Bass and R. E. Riggio, *Transformational leadership,* 2nd ed. Mahwah, N.J.: L. Erlbaum Associates.

[17] F. Franke, J. Felfe, and A. Pundt, “The impact of health-oriented leadership on follower health: Development and test of a new instrument measuring health-promoting leadership,” *Zeitschrift für Personalforschung*, vol. 28, 1-2, pp. 139–161, 2014.

[18] F. Contreras, E. Baykal, and G. Abid, “E-Leadership and Teleworking in Times of COVID-19 and Beyond: What We Know and Where Do We Go,” *Frontiers in Psychology*, vol. 11, p. 590271, 2020, doi: 10.3389/fpsyg.2020.590271.

[19] S. K. Parker, C. Knight, and A. C. Keller, “Remote Managers Are Having Trust Issues,” *Harvard Business Review*, 2020. [Online]. Available: https://hbr.org/2020/07/remote-managers-are-having-trust-issues

[20] M. M. Montoya-Weiss, A. P. Massey, and M. Song, “Getting it together: Temporal coordination and conflict management in virtual teams,” *Academy of Management Journal*, vol. 44, no. 6, pp. 1251–1262, 2001, doi: 10.2307/3069399.

[21] C. W. Rudolph, L. R. Murphy, and H. Zacher, “A systematic review and critique of research on “healthy leadership",” *Leadership Quarterly*, vol. 31, no. 1, p. 101335, 2020, doi: 10.1016/j.leaqua.2019.101335.

[22] F. Pundt and J. Felfe, *HOL. An instrument to assess health-oriented leadership*. Göttingen: Hogrefe, 2017.

[23] A. Bandura, *Social Learning Theory*. New York: General Learning Press, 1971.

[24] R. Nydegger and L. Nydegger, “Challenges In Managing Virtual Teams,” *Journal of Business & Economics Research*, vol. 8, no. 3, 2010, doi: 10.19030/jber.v8i3.690.

[25] S. Park and Y. J. Cho, “Does telework status affect the behavior and perception of supervisors? Examining task behavior and perception in the telework context,” *International Journal of Human Resource Management*, pp. 1–26, 2020, doi: 10.1080/09585192.2020.1777183.

[26] S. Kauffeld, L. Handke, and J. Straube, “Verteilt und doch verbunden: Virtuelle Teamarbeit,” *Gruppe. Interaktion. Organisation. Zeitschrift für Angewandte Organisationspsychologie (GIO)*, vol. 47, no. 1, pp. 43–51, 2016, doi: 10.1007/s11612-016-0308-8.

[27] E. Darics, “E-Leadership or “How to Be Boss in Instant Messaging?” The Role of Nonverbal Communication,” *International Journal of Business Communication*, vol. 57, no. 1, pp. 3–29, 2020, doi: 10.1177/2329488416685068.

[28] L. M. Maruping and R. Agarwal, “Managing team interpersonal processes through technology: a task-technology fit perspective,” *Journal of Applied Psychology*, vol. 89, no. 6, pp. 975–990, 2004, doi: 10.1037/0021-9010.89.6.975.

[29] G. Hertel, S. Geister, and U. Konradt, “Managing virtual teams: A review of current empirical research,” *Human Resource Management Review*, vol. 15, no. 1, pp. 69–95, 2005, doi: 10.1016/J.HRMR.2005.01.002.

[30] B. J. Avolio, S. Kahai, and G. E. Dodge, “E-leadership,” *Leadership Quarterly*, vol. 11, no. 4, pp. 615–668, 2000, doi: 10.1016/S1048-9843(00)00062-X.

[31] B. Lal, Y. K. Dwivedi, and M. Haag, “Working from Home During Covid-19: Doing and Managing Technology-enabled Social Interaction With Colleagues at a Distance,” *Information Systems Frontiers: A Journal of Research and Innovation*, pp. 1–18, 2021, doi: 10.1007/s10796-021-10182-0.

[32] L. A. Hambley, T. A. O’Neill, and T. J. Kline, “Virtual team leadership: The effects of leadership style and communication medium on team interaction styles and outcomes,” *Organizational Behavior and Human Decision Processes*, vol. 103, no. 1, pp. 1–20, 2007, doi: 10.1016/j.obhdp.2006.09.004.

[33] B. A. Lautsch, E. E. Kossek, and S. C. Eaton, “Supervisory approaches and paradoxes in managing telecommuting implementation,” *Human Relations*, vol. 62, no. 6, pp. 795–827, 2009, doi: 10.1177/0018726709104543.

[34] C. D. Cramton, “The Mutual Knowledge Problem and Its Consequences for Dispersed Collaboration,” *Organization Science*, vol. 12, no. 3, pp. 346–371, 2001, doi: 10.1287/orsc.12.3.346.10098.

[35] C. H. Antoni and C. J. Syrek, “Digitalisierung der Arbeit: Konsequenzen für Führung und Zusammenarbeit,” *Gruppe. Interaktion. Organisation. Zeitschrift für Angewandte Organisationspsychologie (GIO)*, vol. 48, no. 4, pp. 247–258, 2017, doi: 10.1007/s11612-017-0391-5.

[36] B. Lal and Y. K. Dwivedi, “Homeworkers' usage of mobile phones; social isolation in the home-workplace,” *Journal of Enterprise Information Management*, vol. 22, no. 3, pp. 257–274, 2009, doi: 10.1108/17410390910949715.

[37] T. D. Allen, T. D. Golden, and K. M. Shockley, “How Effective Is Telecommuting? Assessing the Status of Our Scientific Findings,” *Psychological Science in the Public Interest*, vol. 16, no. 2, pp. 40–68, 2015, doi: 10.1177/1529100615593273.

[38] A. J. Kaluza, F. Weber, R. van Dick, and N. M. Junker, “When and how health-oriented leadership relates to employee well-being—The role of expectations, self-care, and LMX,” *Journal of Applied Social Psychology*, vol. 51, no. 4, pp. 404–424, 2021, doi: 10.1111/jasp.12744.

[39] S. Pischel and J. Felfe, “„Should I Tell my Leader or Not?“ – Health-oriented Leadership and Stigma as Antecedents of Employees‘ Mental Health Information Disclosure Intentions at Work,” *Journal of Occupational and Environmental Medicine*, 2022, doi: 10.1097/JOM.0000000000002688.

[40] J. Felfe, F. Pundt, and A. Krick, “Gesundheitsförderliche Führung = Ressource für Beschäftigte - Belastung für Führungskräfte?,” in *Der Wert der Arbeit: Festschrift zur Verabschiedung von Eva Bamberg*, C. Busch, A. Ducki, J. Dettmers, and H. Witt, Eds., 1st ed., Augsburg, München: Rainer Hampp Verlag, 2017, pp. 241–255.

[41] K. Klug, J. Felfe, and A. Krick, “Caring for Oneself or for Others? How Consistent and Inconsistent Profiles of Health-Oriented Leadership Are Related to Follower Strain and Health,” *Frontiers in Psychology*, vol. 10, p. 2456, 2019, doi: 10.3389/fpsyg.2019.02456.

[42] K. Klug, J. Felfe, and A. Krick, “Does Self-Care Make You a Better Leader? A Multisource Study Linking Leader Self-Care to Health-Oriented Leadership, Employee Self-Care, and Health,” *International Journal of Environmental Research and Public Health*, vol. 19, no. 11, p. 6733, 2022, doi: 10.3390/ijerph19116733.

[43] A. Santa Maria, C. Wolter, B. Gusy, D. Kleiber, and B. Renneberg, “The impact of health-oriented leadership on police officers’ physical health, burnout, depression and well-being,” *Policing: A Journal of Policy and Practice*, vol. 13, no. 2, pp. 186–200, 2019, doi: 10.1093/police/pay067.

[44] D. Horstmann, “Enhancing employee self-care,” *European Journal of Health Psychology*, vol. 25, no. 3, pp. 96–106, 2018, doi: 10.1027/2512-8442/a000014.

[45] L. A. Grimm, G. F. Bauer, and G. J. Jenny, “Is the health-awareness of leaders related to the working conditions, engagement, and exhaustion in their teams? A multi-level mediation study,” *BMC Public Health*, vol. 21, no. 1, p. 1935, 2021, doi: 10.1186/s12889-021-11985-1.

[46] M. Arnold and T. Rigotti, “The Leader in the Spotlight: Health-Oriented Leadership and its Antecedents and Outcomes,” *Academy of Management Proceedings*, vol. 2020, no. 1, p. 16724, 2020, doi: 10.5465/AMBPP.2020.16724abstract.

[47] L. Klebe, K. Klug, and J. Felfe, “The show must go on: The effects of crisis on health-oriented leadership and follower exhaustion during Covid-19 pandemic,” *Zeitschrift für Arbeits- und Organisationspsychologie*, vol. 65, pp. 231–243, 2021, doi: 10.1026/0932-4089/a000369.

[48] I. Efimov, V. Harth, and S. Mache, “Health-Oriented Self- and Employee Leadership in Virtual Teams: A Qualitative Study with Virtual Leaders,” *International Journal of Environmental Research and Public Health*, vol. 17, no. 18, p. 6519, 2020, doi: 10.3390/ijerph17186519.

[49] T. Müller and C. Niessen, “Self-leadership and self-control strength in the work context,” *Journal of Managerial Psychology*, vol. 33, no. 1, pp. 74–92, 2018. [Online]. Available: https://doi.org/10.1108/JMP-04-2017-0149

[50] C. Kranabetter and C. Niessen, “Managers as role models for health: Moderators of the relationship of transformational leadership with employee exhaustion and cynicism,” *Journal of Occupational Health Psychology*, vol. 22, no. 4, pp. 492–502, 2017, doi: 10.1037/ocp0000044.

[51] S. Hauff, A. Krick, L. Klebe, and J. Felfe, “High-Performance Work Practices and Employee Wellbeing—Does Health-Oriented Leadership Make a Difference?,” *Frontiers in Psychology*, vol. 13, 2022, doi: 10.3389/fpsyg.2022.833028.

[52] A. Klamar, J. Felfe, A. Krick, S. Röttger, K.-H. Renner, and M. Stein, “Die Bedeutung von gesundheitsförderlicher Führung und Commitment für die Mitarbeitergesundheit [Significance of health-oriented leadership and commitment for employees’ health],” *Wehrmedizinische Monatsschrift*, vol. 62, no. 8, 2018.

[53] A. Krick, J. Felfe, and S. Pischel, “Health-oriented leadership as a job resource: can staff care buffer the effects of job demands on employee health and job satisfaction?,” *Journal of Managerial Psychology*, vol. 37, no. 2, pp. 139–152, 2022, doi: 10.1108/JMP-02-2021-0067.

[54] M. Arnold and T. Rigotti, “Is it Getting Better or Worse? Health-Oriented Leadership and Psychological Capital as Resources for Sustained Health in Newcomers,” *Applied Psychology*, 2020, doi: 10.1111/apps.12248.

[55] D. Horstmann and S. Remdisch, “Gesundheitsorientierte Führung in der Altenpflege,” *Zeitschrift für Arbeits- und Organisationspsychologie*, vol. 60, no. 4, pp. 199–211, 2016, doi: 10.1026/0932-4089/a000223.

[56] C. Köppe, J. Kammerhoff, and A. Schütz, “Leader-follower crossover: exhaustion predicts somatic complaints via StaffCare behavior,” *Journal of Managerial Psychology*, vol. 33, no. 3, pp. 297–310, 2018, doi: 10.1108/JMP-10-2017-0367.

[57] A. Santa Maria, C. Wolter, B. Gusy, D. Kleiber, and B. Renneberg, “Reducing work-related burnout among police officers: The impact of job rewards and health-oriented leadership,” *The Police Journal: Theory, Practice and Principles*, vol. 94, no. 3, pp. 406–421, 2021, doi: 10.1177/0032258X20946805.

[58] L. Klebe, J. Felfe, and K. Klug, “Healthy Leadership in Turbulent Times: The Effectiveness of Health-Oriented Leadership in Crisis,” *British Journal of Management*, vol. 32, no. 4, pp. 1203–1218, 2021, doi: 10.1111/1467-8551.12498.

[59] A. J. Kaluza, S. C. Schuh, M. Kern, K. Xin, and R. Dick, “How do leaders' perceptions of organizational health climate shape employee exhaustion and engagement? Toward a cascading-effects model,” *Human Resource Management*, vol. 59, no. 4, pp. 359–377, 2020, doi: 10.1002/hrm.22000.

[60] R. Vonderlin *et al.,* “Health-Oriented Leadership and Mental Health From Supervisor and Employee Perspectives: A Multilevel and Multisource Approach,” *Frontiers in Psychology*, vol. 11, p. 614803, 2020, doi: 10.3389/fpsyg.2020.614803.

[61] A. Krick, J. Felfe, and K. Klug, “Turning intention into participation in OHP courses? The moderating role of organizational, intrapersonal and interpersonal factors,” *Journal of Occupational and Environmental Medicine*, vol. 61, no. 10, pp. 779–799, 2019.

[62] L. Klebe, J. Felfe, A. Krick, and S. Pischel, “The shadows of digitization: On the losses of health-oriented leadership in the face of ICT hassles,” *Behaviour & Information Technology*, in review.

[63] A. J. Kaluza and N. M. Junker, “Caring for yourself and for others: team health climate and self-care explain the relationship between health-oriented leadership and exhaustion,” *Journal of Managerial Psychology*, vol. 37, no. 7, pp. 655–668, 2022, doi: 10.1108/JMP-10-2021-0567.

[64] A. Bregenzer, J. Felfe, S. Bergner, and P. Jiménez, “How followers’ emotional stability and cultural value orientations moderate the impact of health-promoting leadership and abusive supervision on health-related resources,” *German Journal of Human Resource Management: Zeitschrift für Personalforschung*, vol. 33, no. 4, pp. 307–336, 2019, doi: 10.1177/2397002218823300.

[65] J. R. B. Halbesleben, J.-P. Neveu, S. C. Paustian-Underdahl, and M. Westman, “Getting to the “COR”,” *Journal of Management*, vol. 40, no. 5, pp. 1334–1364, 2014, doi: 10.1177/0149206314527130.

[66] A. Bregenzer and P. Jimenez, “Risk Factors and Leadership in a Digitalized Working World and Their Effects on Employees' Stress and Resources: Web-Based Questionnaire Study,” *Journal of Medical Internet Research*, vol. 23, no. 3, e24906, 2021, doi: 10.2196/24906.

[67] A. B. Bakker and W. B. Schaufeli, “Burnout Contagion Processes Among Teachers,” *Journal of Applied Social Psychology*, vol. 30, no. 11, pp. 2289–2308, 2000, doi: 10.1111/j.1559-1816.2000.tb02437.x.

[68] N. Wirtz, T. Rigotti, K. Otto, and C. Loeb, “What about the leader? Crossover of emotional exhaustion and work engagement from

followers to leaders," *Journal of Occupational Health Psychology*, vol. 22, no. 1, pp. 86–97, 2017, doi: 10.1037/ocp0000024.

[69] A. B. Bakker and E. Demerouti, "The Job Demands-Resources model: state of the art," *Journal of Managerial Psychology*, vol. 22, no. 3, pp. 309–328, 2007, doi: 10.1108/02683940710733115.

[70] S. E. Hobfoll, "Conservation of resources theory: its implication for stress, health, and resilience," in *The Oxford Handbook of Stress, Health, and Coping*, S. Folkman, Ed., New York: Oxford University Press, 2012, 127-147.

[71] A. Krick, J. Felfe, S. Hauff, and K.-H. Renner, "Facilitating Health-Oriented Leadership from a Leader's Perspective: Antecedents at the Organizational, Workplace, and Individual Level," *Zeitschrift für Arbeits- und Organisationspsychologie*, vol. 66, no. 4, pp. 213–225, 2022, doi: 10.1026/0932-4089/a000397.

[72] S. Pischel, J. Felfe, and A. Krick, "Health-Oriented Leadership: Antecedents of Leaders' Awareness Regarding Warning Signals of Emerging Depression and Burnout," *German Journal of Human Resource Management: Zeitschrift für Personalforschung*, 239700222211307, 2022, doi: 10.1177/23970022221130754.

[73] L. Klebe, J. Felfe, and K. Klug, "Mission impossible? Effects of crisis, leader and follower strain on health-oriented leadership," *European Management Journal*, vol. 40, no. 3, pp. 384–392, 2022, doi: 10.1016/j.emj.2021.07.001.

[74] C. Köppe and A. Schütz, "Healthy Leaders: Core Self-Evaluations Affect Leaders' Health Behavior Through Reduced Exhaustion," *Frontiers in Psychology*, vol. 10, p. 998, 2019, doi: 10.3389/fpsyg.2019.00998.

[75] A. Krick, I. Wunderlich, and J. Felfe, "Gesundheitsförderliche Führungskompetenz entwickeln," in *Handbuch Gesundheitsförderung bei der Arbeit: Interventionen für Individuen, Teams und Organisationen*, A. Michel and A. Hoppe, Eds., Wiesbaden: Springer, 2022, pp. 213–231.

[76] R. Vonderlin *et al.,* "Effectiveness of a mindfulness- and skill-based health-promoting leadership intervention on supervisor and employee levels: A quasi-experimental multisite field study," *Journal of Occupational Health Psychology*, vol. 26, no. 6, pp. 613–628, 2021, doi: 10.1037/ocp0000301.

[77] G. Elprana, J. Felfe, and F. Franke, "Gesundheitsförderliche Führung diagnostizieren und umsetzen," in *Handbuch Mitarbeiterführung: Wirtschaftspsychologisches Praxiswissen für Fach- und Führungskräfte*, J. Felfe and R. van Dick, Eds., Berlin, Heidelberg: Springer, 2016, pp. 143–156.

[78] J. Felfe, A. Krick, and A. Ducki, "Gesundheitsförderliche Führung erfolgreich umsetzen," in *Wandel gestalten – Herausforderungen und Ergebnisse der empirischen Managementforschung*, S. Bergner, J. Fleiß, and A. Gutschelhofer, Eds., Graz: Grazer Universitätsverlag & Leykam, 2019, pp. 23–41.

[79] F. Stuber *et al.,* "The effectiveness of health-oriented leadership interventions for the improvement of mental health of employees in the health care sector: a systematic review," *International Archives of Occupational and Environmental Health*, vol. 94, no. 2, pp. 203–220, 2021, doi: 10.1007/s00420-020-01583-w.

[80] I. Dannheim, H. Ludwig-Walz, A. E. Buyken, V. Grimm, and A. Kroke, "Effectiveness of health-oriented leadership interventions for improving health and wellbeing of employees: a systematic review," *Journal of Public Health*, 2021, doi: 10.1007/s10389-021-01664-1.

Führungskulturen im digitalen Zeitalter. Der Fall der Bundeswehr

Cristina Besio*, Cornelia Fedtke, Christine Posner
Professur für Organisationssoziologie
Helmut-Schmidt-Universität,
Universität der Bundeswehr Hamburg
Deutschland
cristina.besio@hsu-hh.de

in Kooperation mit Gabi Dreo Rodosek
Professur Kommunikationssysteme und Netzsicherheit
Universität der Bundeswehr München
Deutschland
gabi.dreo@unibwm.de

Kurzfassung **– Die Digitalisierung gewinnt in der Bundeswehr sowohl im Verwaltungshandeln als auch in militärischen Operationen beim Betrieb militärischer Waffensysteme zunehmend an Bedeutung. Dabei verändert die Nutzung digitaler Infrastrukturen die alltägliche Arbeit tiefgreifend, eröffnet neue Chancen, birgt aber auch Risiken. Im Prozess der digitalen Transformation sind sowohl bei der Einführung als auch bei der Anwendung Widerstände und Akzeptanzprobleme zu beobachten. Vor diesem Hintergrund untersuchen wir insbesondere am Beispiel der Nutzung datenintensiver Algorithmen, wie organisationskulturelle und technische Faktoren die Digitalisierung der Streitkräfte beeinflussen. Dabei möchten wir klären, welche Gründe dazu führen, dass die großen Datenmengen, über die die Bundeswehr verfügt und die sie fortlaufend produziert, nur ansatzweise genutzt werden. Wir untersuchen insbesondere die Wechselwirkungen zwischen der Anwendung von Data Analytics und der Führungskultur in der Bundeswehr und richten den Fokus auf die soziale Dimension der Digitalisierung in ihren verschiedenen Facetten.**
Im Projekt „Führungskulturen im digitalen Zeitalter. Der Fall der Bundeswehr“ *FüKu.Bw* verknüpfen wir Forschungen in den Feldern Software Engineering mit organisations- und führungssoziologischen Fragen. Auf Basis einer interdisziplinären Analyse werden Handlungsempfehlungen für die Einführung und Nutzung von IT-Systemen sowie für die Weiterentwicklung der Führungskultur erarbeitet. Das Projekt mit einer Laufzeit von April 2021 bis März 2024 befindet sich aktuell am Beginn des zweiten Jahres. Wir berichten in diesem Beitrag Ergebnisse aus insgesamt 20 qualitativen Interviews mit Expertinnen und Experten, die maßgeblich an der digitalen Transformation der Bundeswehr beteiligt sind sowie erste Erkenntnisse aus themenzentrierten Interviews und teilnehmenden Beobachtungen in zwei Organisationsbereichen der Bundeswehr.

Stichworte – Digitalisierung, Big Data Analytics, digitales Mindset, militärische Führung, sozialer Prozess

NOMENKLATUR

BAAINBw	Bundesamt für Ausrüstung Informationstechnik und Nutzung der Bundeswehr
BMVg	Bundesministerium der Verteidigung
CIT	Cyber- und Informationstechnik
CIR	Cyber- und Informationsraum
IT	Informationstechnik

I. Digitale Transformation in der Bundeswehr

Die digitale Transformation prägt als Megatrend das aktuelle Zeitalter (u.a. Rumpp, Eilers 2021, Enste et a. 2020, Faber 2018). Auch in der Bundeswehr gewinnt die Digitalisierung zunehmend an Bedeutung. Für eine militärische Organisation wie die Bundeswehr sind die Herausforderungen, die die Digitalisierung mit sich bringt, aufgrund ihrer Größe und ihres speziellen Auftrags besonders. Neben den Kernauftrag der zunehmend wichtiger werdenden Landes- und Bündnisverteidigung und die Aufgabe als Einsatzarmee in der internationalen Konfliktverhütung und Krisenbewältigung sowie den Heimatschutz ist die Aufgabe der Minderung von Cyber-Attacken und der Abwehr hybrider Bedrohungen getreten (vgl. Posner 2021).

Für die Bundeswehr als eine der größten Organisationen Deutschlands ist die Digitalisierung nach wie vor eine Herkules-Aufgabe. Obwohl das gleichnamige IT-Projekt zur Modernisierung der nicht-militärischen Informations- und Kommunikationstechnologie bereits 2016 abgeschlossen wurde, ist der Digitalisierungsprozess bei weitem nicht beendet. Vielmehr ist die Digitalisierung militärischer Waffensysteme in all ihren Facetten noch hinzugekommen. Aufgrund der rasanten technologischen Entwicklungen ist die Digitalisierung somit zu einer immerwährenden Aufgabe geworden, die in zahlreichen Projekten wahrgenommen wird (vgl. BAAINBw, Pressemitteilung vom 28.12.2020). Während auf der einen Seite die Digitalisierung verschiedener Organisationsbereiche immer weiter voranschreitet, zeigt sich auf der anderen Seite, dass bereits bestehende digitale Lösungen nicht (vollends) ausgeschöpft werden. Digitale Infrastrukturen werden von den Soldatinnen und Soldaten nach wie vor nicht immer oder zumindest nicht optimal genutzt, und es bestehen weiterhin Akzeptanzprobleme, Widerstände und Einführungshemmnisse in Bezug auf digitale Technologien.

In den konzeptionellen Dokumenten für den Geschäftsbereich des BMVg ist die Überzeugung, dass Digitalisierung eine Notwendigkeit für die Auftragserfüllung ist, stark verankert. Der Digitalisierung wird insgesamt eine herausgehobene Bedeutung beigemessen und ihr Gelingen wird als ausschlaggebender Faktor für die Zukunftsfähigkeit hervorgehoben (vgl. BMVg 2015, S. 4). Prägend für die Zielsetzungen sind die Einsatzorientierung, die Bundeswehrgemeinsamkeit sowie die Bündnisorientierung, die jeweils umfangreiche und teilweise

https://doi.org/10.24405/14577

spezifische Herausforderungen mit sich bringen. Konkrete Ziele, die mit der Digitalisierung verfolgt werden, sind im militärischen Bereich etwa die Entwicklung bundeswehrgemeinsamer digitaler Lagebilder, die Befähigung zur vernetzten Operationsführung (NetOpFü) sowie die Förderung von IT-Innovationen, die gezielt für die Weiterentwicklung der Fähigkeiten der Streitkräfte nutzbar gemacht werden sollen. Hier werden Verbesserungen in der zukünftigen Operationsführung sowie den Einsatzgrundsätzen und den Kampfweisen gesehen (vgl. BMVg 2019, S. 5). Mit dem Sonderprogramm „Resilienz der Bundeswehr durch Digitalisierung" (BMVg 2021) soll insbesondere konsequent die Einsatzbereitschaft der Bundeswehr verbessert werden. Insgesamt ist es notwendig, für alle Aufgabenbereiche leistungsfähige IT bereitzustellen. Die Arbeitsplätze sollen jeweils bedarfsorientiert digital und mobil ausgestattet werden, so dass moderne Formen der Kommunikation und Kollaboration sowie der schnelle Zugriff auf alle relevanten Informationen ermöglicht wird. Digitalisierung soll im Verwaltungshandeln in der Unterstützung von Prozessen und für die Neugestaltung von Abläufen dienen. Erwartet werden Effizienzsteigerungen und Synergieeffekte: „Für die Streitkräfte ist die Digitalisierung der Schlüssel zur Informations-, Führungs- und Wirkungsüberlegenheit wie auch zur Verbesserung der Durchsetzungs- und Reaktionsfähigkeit." (BMVg 2019, S. 3)

II. Das Projekt: „Führungskulturen im digitalen Zeitalter. Der Fall der Bundeswehr" *FüKu.Bw*

Vor diesem Hintergrund untersuchen wir Digitalisierungsprozesse in der Bundeswehr und fokussieren uns vor allem auf die soziale Dimension von Digitalisierung. Die Betrachtung der Einführung neuer Techniken in Organisationen als einen durchgehend und genuin sozialen Prozess eröffnet neue Perspektiven auf die aufgeworfenen Problematiken. Auf der einen Seite können die bereits existierenden Kulturen und Strukturen die Einführung neuer Techniken erleichtern oder hindern (Orlikowski 2000). Aber auf der anderen Seite haben neue Techniken auch das Potential die sozialen Verhältnisse empfindlich zu stören sowie Normen und Strukturen zu verändern (Leonardi 2011). Im Hinblick auf die Digitalisierung sind daher weitreichende Folgen insbesondere für Organisationen zu erwarten, weil Digitalisierung an die essentiellen Strukturen von Organisationen, wie unter anderem die Wissensordnung, Legitimationsprozesse und Machtverhältnisse rührt und diese neugestalten kann (u.a. Besio et al. 2022; Büchner 2018; Faraj et al. 2018).

In unserem Forschungsprojekt setzen wir einen speziellen Fokus auf den Bereich datenintensiver Algorithmen in einer militärischen Organisation. Dabei betten wir nicht nur die Einführung solcher Techniken in den gesamten Prozess der Digitalisierung der Bundeswehr ein, sondern nehmen auch die spezifischen Herausforderungen, die diese Techniken mit sich bringen, in den Blick. Wir untersuchen, welche organisationskulturellen und technischen Faktoren den Umgang mit Data Analytics Tools in der Bundeswehr beeinflussen und wie diese Technik wiederum die Organisation verändert. Insbesondere behandeln wir die Wechselwirkungen zwischen Data Analytics und der Führungskultur in der Bundeswehr. Dabei leiten uns die folgenden Forschungsfragen:

- Wie verändern datenintensive Algorithmen Führungsprozesse und -kulturen?
- Wie beeinflussen Organisationsstrukturen und -kulturen die Einführung und Nutzung von datenintensiven Algorithmen in der Bundeswehr?
- Wie kann die Einführung von datenintensiven Algorithmen durch technische und managerielle Lösungen unterstützt werden?

In Anlehnung an die Verfahrensweisen der Grounded Theory (Straus, Corbin 1996) greifen wir auf die in den Strategiepapieren formulierten Ziele zur Nutzung datenintensiver Algorithmen zurück. Wir analysieren die berichteten Erfahrungen von 20 Expertinnen und Experten zum digitalen Transformationsprozess der Bundeswehr inhaltsanalytisch und identifizieren dabei insbesondere die dahinterstehenden sozialen Prozesse. Kontrastiert und vertieft werden diese Erkenntnisse zu ausgewählten Anwendungsfeldern durch themenzentrierte Interviews mit Nutzerinnen und Nutzern spezieller Tools.

III. Prozess der Digitalisierung in der Bundeswher

Die konzeptionellen Dokumente für den Geschäftsbereich des BMVg können als wegweisende Momente der Digitalisierung der Organisation verstanden werden, da sie beschreiben wie genau die Digitalisierung in der Organisation von statten gehen und sie formen soll. Mit diesen Vorgaben wird ein Rahmen für die letztliche Ausgestaltung der Digitalisierung gesetzt (vgl. BMVg 2021).

Mit den beschriebenen relevanten Veränderungen, die die Digitalisierung auf vielen Ebenen für die Bundeswehr erwarten lässt, sind Anpassungen der Organisation erforderlich. Aufgrund der Heterogenität der Organisation ist der Prozess der Digitalisierung allerdings unterschiedlich weit vorangeschritten. Die vielfältigen Bereiche der Organisation haben unterschiedliche Aufgaben und verfolgen somit auch verschiedene Zwecke und Ziele, die von der Optimierung der Verwaltung, über die Beschleunigung und Verschlankung von Prozessen sowie die Befähigung zu kollaborativen und flexiblen Arbeitsformen bis hin zur konsequenten Digitalisierung militärischer Anwendungen mit den speziellen Anforderungen der einzelnen TSKs und unterschiedlichster Waffensysteme reichen. Die Varianz der Ausgangssituationen und Bedarfe ist dementsprechend groß.

Unsere Experteninterviews zeigen, dass diese organisationale Verschiedenheit sich gleichzeitig darin widerspiegelt, dass es kein einheitliches, allgemeingültiges Verständnis von „Digitalisierung" gibt und was sie umfassen sollte. Vielmehr deckt die Varianz im Verständnis von Digitalisierung ein weites Feld ab, dass bei der Ausstattung mit Computern beginnt und sich bis zur automatischen Auswertung von großen Datenmengen durch tiefe neuronale Netze erstreckt. Das Verständnis einer Technologie sowie deren Bewertung ist aber ein essentieller sozialer Moment mit zahlreichen Folgen. Denn das vorherrschende Verständnis darüber, was eine Technik, in diesem Fall Digitalisierung, ist und ausmacht, ist für die gegenwärtige Gestaltung von Prozessen der Digitalisierung maßgeblich.

Die große Heterogenität in der Organisation sowie das unterschiedliche Verständnis von Digitalisierung haben als Konsequenz, dass zahlreiche Einzellösungen, die dezentral in den Organisationsbereichen entwickelt worden sind, die ähnliche, teilweise sogar gleiche Funktionen erfüllen, nur schwer aneinander oder an die Gesamtorganisation anzuschließen sind. Daraus ergibt sich das Dilemma, dass einerseits ein Mangel an

Zentralisierung in Bezug auf die verschiedenen Digitalisierungsansätze beklagt wird und andererseits das Bedürfnis besteht, dezentrale Spielräume zu bewahren.

Darüber hinaus wird in unseren Interviews mit Expertinnen und Experten berichtet, dass der Prozess der Digitalisierung insbesondere aufgrund sehr spezifischer organisationaler Strukturen und bestehender Prozesse verlangsamt wird. Häufig wurde vor allem auf die Trägheit der Organisation selbst und auf komplexe, langwierige Beschaffungsprozesse hingewiesen. Das dies auch anders sein kann, zeigt die weit verbreitete Auffassung, dass die Corona-Pandemie zu einer deutlichen Beschleunigung der digitalen Transformation in der Bundeswehr geführt hat, indem eine weitgehende Ausstattung mit Technik für die Arbeit im Home-Office erfolgte. Dies ist wichtig, weil die Mikroebene des Personals Digitalisierung stark mit einer flächendeckenden technischen Grundausstattung in Verbindung bringt. Insofern trägt diese Ausstattung dazu bei, den neuen Anforderungen zur mobilen Kommunikation und Home-Office gerecht zu werden, die Möglichkeiten der Aus- und Weiterbildung digitaler Kompetenzen zu erweitern und die positiven Folgen der Digitalisierung für alle direkt wahrnehmbar zu machen.

IV. Data Analytics in der Bundeswehr

Eine relevante Problematik, die in den Strategiepapieren zur digitalen Transformation der Bundeswehr benannt wurde, ist die fortlaufende Produktion großer Datenmengen, die bislang nur ansatzweise genutzt werden (vgl. bspw. BMVg, 2019, S. 30). Dies spiegelt sich in unseren Erkenntnissen aus den qualitativen Interviews wider. Auch die von uns untersuchten Bereiche der Bundeswehr stehen noch relativ am Anfang der Einführung von datenintensiven algorithmischen Verarbeitungsprozessen stehen. Im Rahmen von Pilotprojekten werden einzelne Anwendungen entwickelt, in denen die Analyse großer Datenmengen und datenintensiver Algorithmen erprobt wird. Es handelt sich nicht nur um die Testung technischer Lösungen, sondern um projektförmige Anwendungen, die erkennen lassen, welche organisationalen Herausforderungen mit der Einführung einer Technik verbunden sind.

Eins steht fest: Eine ausgiebigere Nutzung vorhandener Daten könnte wesentlich dazu beitragen, das basale Problem der Datenqualität zu überwinden, welches uns häufig geschildert wurde. Daten sind die essentielle Grundlage algorithmischer Analyse- und Lernprozesse. Die Qualität der Daten bestimmt, welche Informationen letztlich aus ihnen generiert werden können. Damit bilden die Daten die Basis für die organisationalen Prozesse der Wissensbildung. Die Gründe dafür, warum solche Daten nicht oder nur wenig genutzt werden, sind vielfältig und umfassen technische Fragen (etwa bezüglich der Kompatibilität der Datenbanken), rechtliche Problematiken (bezüglich des Datenschutzes) sowie Hindernisse, die mit der Abteilungsstruktur der Organisation zu tun haben.

Wir wollen auf den vorher angesprochenen Aspekt des Verständnisses und der Bewertung von Technik zurückkommen. Denn insbesondere bei der Frage der datenintensiven Algorithmen konnten wir feststellen, dass Digitalisierung bei den Mitgliedern der Organisation verschiedene Zweifel und Ängste auslösen kann. Die Veränderungen, die die Einführung digitaler Technologien mit sich bringen sind keineswegs eindeutig, sondern können für einzelne Mitglieder vielfältige sowohl positive als auch negative Implikationen haben. In Folge unterschiedlicher Vorstellungen und Erwartungen darüber, was mit der Anwendung dieser Tools verbunden ist und was sie leisten können, werden Gegenwart und Zukunft oft diskursiv verwischt, so dass die Gegenwart im Lichte der vorgestellten Konsequenzen für die Zukunft erlebt wird. Insbesondere bei Führungskräften ist die tatsächliche Nutzung von datenintensiven Algorithmen stark geprägt durch die imaginierte Beziehung von Zukunftsvorstellungen über digitale Technik und das eigene Führungsverständnis. Führungskräfte etwa, die Führung als primär zwischenmenschlichen Austausch auffassen, stehen einer automatisierten Informationsverarbeitung und einer Unterstützung ihrer Entscheidungen durch Outputs datenintensiver Algorithmen skeptisch gegenüber und müssen von ihrem Nutzen eher überzeugt werden.

V. Führung in militärischen Organisationen in Zeiten der Digitalisierung

Grundsätzlich trägt auch in der Bundeswehr die Digitalisierung insgesamt aber auch die beginnende Nutzung von Data Analytics dazu bei, das Führungsverhalten zu modernisieren und macht Veränderungen von Führung möglich und notwendig. Der Einsatz digitaler Techniken ermöglicht neue Formen der kooperativen Führung und hat die Voraussetzungen für das Arbeiten im Home-Office geschaffen – auch in der Bundeswehr. Dies hat unmittelbare Auswirkungen auf das gelebte Führungsverhalten, birgt das Potenzial, die Führungskultur zu verändern und beeinflusst den Austausch zwischen Führungskräften und Mitarbeitenden tiefgreifend (vgl. Thiemann 2021).

In der Bundeswehr hat die Führung im digitalen Raum erst langsam begonnen und befindet sich noch in einer frühen Phase, wie uns von den Expertinnen und Experten berichtet wurde. Insgesamt werden die bekannten Vorteile, welche die Digitalisierung mit sich bringt, wie beispielsweise das kollaborative Arbeiten an flexiblen Arbeitsorten sowie das Führen auf Distanz durchaus wahrgenommen. Es werden aber auch Nachteile, wie fehlender persönlicher Kontakt und geringere Kontrollmöglichkeiten für Führungskräfte identifiziert, so dass die Grenzen virtueller Führung genau ausgelotet werden. Insbesondere wurde die Frage des Vertrauens sowohl aus Perspektive der Mitarbeitenden, die sich mehr davon wünschen, als auch aus Sicht der Vorgesetzten thematisiert, die oftmals mit der Problematik konfrontiert sind, dass digitale Führung die Bildung von Vertrauen erschwert. Das Konzept der Führung auf Distanz wird vor allem im militärischen Bereich kritisch betrachtet. Militärische Führung gründet stark auf der Ausbildung interpersonaler Beziehungen (vgl. Keller 2012). Das Vertrauen der Truppe in die Führungsperson und das Gemeinschaftsgefühl untereinander sind aber allein durch digital vermittelte Kommunikation und Arbeitsprozesse nur schwer zu etablieren.

Eine besondere Herausforderung für die militärische Führung stellen datenintensive algorithmische Informationsverarbeitungen dar, deren Ergebnisse in Entscheidungsprozesse einfließen. Bislang wurden insbesondere die Folgen autonomer letaler Waffensysteme und die ethischen Implikationen von Entscheidungen, die durch Maschinen getroffen werden, betrachtet (u.a. Krafft, Zweig 2020, Kraus, Marahrens 2020). Die Einsatzmöglichkeiten datenintensiver Algorithmen gehen jedoch weit darüber hinaus und müssen in Bezug auf Führung insgesamt in den Blick genommen werden (vgl. Posner 2021). Durch die Anwendung solcher Tools können Informationen an vielen Stellen direkter verfügbar sein. So ergibt sich die neue Situation einer schnelleren und besseren Informiertheit auf unterschiedlichen Ebenen der Organisation, die durch kurze Informationswege und die unmittelbare Verfügbarkeit von Daten entsteht. Der große Mehrwert dieser Anwendungen wird in der Vorbereitung informierter Entscheidungen verortet. Jedoch treten die neuen Tools zu traditionellen Informationswegen über die hierarchische Ordnung in Konkurrenz und können bestehende Strukturen irritieren und vorhandene Machtverhältnisse in Frage stellen (vgl. Muster et al. 2020, Büchner 2018).

In unseren Interviews werden verschiedene Folgen der Einführung datenintensiver Algorithmen genannt. Teilweise sind diese Effekte schon eingetreten, teilweise hat man vielmehr mit Ängsten und Vorbehalten zu tun. Weit verbreitet ist etwa die Überzeugung, dass die neue, umfassende Informationslage dazu verleitet, auf einzelnen Ebenen in der Führungsstruktur, das Handeln der Mitarbeitenden genauer zu monitoren und Mikromanagement zu betreiben. Zudem eröffnet die Verfügbarkeit umfassender und aktueller Informationen über Hierarchieebenen hinweg das Risiko einer Zentralisierung von (taktischen) Entscheidungen. Die Befürchtung ist, dass die Spitze der Hierarchie Entscheidungen, die vormals auf anderen Ebenen getroffen wurden, an sich ziehen könnte. Ein weiteres zentrales und damit verbundenes Problem, welches wir identifizieren konnten ist, dass bei den Führungskräften nicht immer das Verständnis für den Nutzen datenintensiver Softwareanwendungen vorhanden ist und sie nicht immer nachvollziehen können, wie und für welche Fragen sie die Outputs der Algorithmen einsetzen sollen. Die Frage nach dem Verständnis hängt eng mit der Frage des Vertrauens zusammen, die in Bezug auf Data Analytics ebenfalls problematisch ist. Denn für militärische Führungskräfte sind vor allem die gelebten Erfahrungen sowie der persönliche Austausch relevant; datenintensive Algorithmen hingegen liefern sachliche Werte und datengestützte Erkenntnisse, die auf sehr spezifische Aufgaben(-bereiche) bezogen sind. Wie das Vertrauen in diese Tools und ihre Ergebnisse erzeugt werden kann, ist offen. Datenintensive Algorithmen ermöglichen nicht nur Zentralisierung, sondern können genutzt werden, um Informationen auch auf untere Ebenen zu zirkulieren. Dies schafft eine wichtige Bedingung, um die viel gepriesenen Formen partizipativer bzw. agiler Führung (vgl. Hofmann, Wienken 2020, Rumpp, Zapp, Eilers 2017) einzuführen. So wundert es nicht, dass im Zuge der Digitalisierung in einzelnen Organisationsbereichen bereits heute sehr viel direkter über Hierarchieebenen hinweg kommuniziert wird, was allerdings im taktisch-operativen Bereich Gefahren mit sich bringen kann.

Insgesamt ist die Bundeswehr bereits heute von der Überzeugung geprägt, dass Führung und Digitalisierung eng miteinander zusammenhängen. In einer stark hierarchisch strukturierten Organisation spielen die Führungskräfte über alle Ebenen hinweg eine wichtige Rolle zur Gestaltung der Digitalisierung. Dabei sind ihre Erwartungen, Ängste und Bewertungen gegenüber digitalen Anwendungen, aber auch ihr gelebtes Beispiel und ihr konkretes Führungsverhalten in einer digitalen Umgebung von Bedeutung. Dies findet in dem viel zitierten ‚digitalen Mindset' Ausdruck, welches weiterentwickelt werden muss. Das Gelingen der digitalen Transformation ist damit wesentlich von der Ausgestaltung der Führung, die den Prozess begleitet, abhängig.

DANKSAGUNG

Die Autorinnen bedanken sich für die Förderung des Projekts „Führungskulturen im digitalen Zeitalter. Der Fall der Bundeswehr" *FüKu.Bw* bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr.

LITERATUR

[1] Besio, Cristina; Fedtke, Cornelia; Pronzini, Andrea (2022) Veränderungen organisationaler Legitimationsmuster durch Digitalisierung. In: Onnen, Corinna; Stein-Redent, Rita; Blättel-Mink, Birgit; Noack, Torsten; Opielka, Michael; Späte, Katrin (Hrsg.) Organisationen in Zeiten der Digitalisierung. Springer VS.

[2] BMVg (2015) IT-Strategie des Geschäftsbereichs BMVg. https://fragdenstaat.de/anfrage/it-strategie-des-geschaftsbereichs-bmvg-vom-02122015/50759/anhang/fds_it_strategie_bmvg_20160517.pdf

[3] BMVg (2017) Strategische Leitlinie Digitalisierung. S. 7 https://www.bundeswehr.de/resource/blob/66394/4bbd6bd8 e0fe81 df975480a081bd1a37/StrattLL%20Digitalisierung-V1-H-20170412.pdf

[4] BMVg (2019) Umsetzungsstrategie Digitale Bundeswehr.

[5] BMVg (2021) Dritter Bericht zur Digitalen Transformation des Geschäftsbereichs des Bundesministeriums der Verteidigung. https://www.bmvg.de/de/aktuelles/dritter-digitalbericht-veroeffentlicht-5060306

[6] Büchner, Stefanie (2018) Zum Verhältnis von Digitalisierung und Organisation. In: Zeitschrift für Soziologie, 47(5), 332-348. DOI: https://doi.org/10.1515/zfsoz-2018-0121

[7] Enste, Dominik H.; Kürten, Louisa Marie; Suling, Lena; Orth, Anja Katrin (2020) Digitalisierung und mitarbeiterorientierte Führung. Die Bedeutung der Kontrollüberzeugung für die Personalpolitik. IW-Analysen 135. http://hdl.handle.net/10419/214160

[8] Faber, Oliver (2018) Digitalisierung - ein Megatrend: Treiber Technologische Grundlagen. S. 3-42 in: Erner, Michael (Hrsg.), *Management 4.0 – Unternehmensführung im digitalen Zeitalter*, https://doi.org/10.1007/978-3-662-57963-3_1

[9] Faraj, Samer; Pachidi, Stella; Sayegh, Karla (2018): Working and Organizing in the Age of the Learning Algorithm. In: Information and Organization 28(1), 62-70. https://doi.org/10.1016/j.infoandorg.2018.02.005

[10] Hofmann, Josephine; Wienken, Valerie (2020) FÜHRUNG IN DER DIGITALEN TRANSFORMATION Ein Realitätscheck für mittelständische Unternehmen. Hrsg.: Bauer, Wilhelm; Riedel, Oliver; Weisbecker, Anette; Rief, Stefan in Kooperation und im Auftrag von Rochus Mommert. http://publica.fraunhofer.de/documents/N-599911.html

[11] Keller, Jörg (2012): Führung und Führer im Militär. In: Leonhard, Nina; Werkner, Ines-Jacqueline (Hrsg.): Militärsoziologie – Eine Einführung. Wiesbaden: Springer VS, 475 – 493. DOI: 10.1007/978-3-531-93456-3_20

[12] Krafft, Tobias D.; Zweig, Katharina A. (2020) Herausforderungen bei der Nutzung von KI in militärischen Anwendungsgebieten. S. 55-66 in: Rogg, Matthias; Scheidt, Sophie; von Schubert, Hartwig (Hrsg.) Ethische Herausforderungen digitalen Wandels in bewaffneten Konflikten. https://d-nb.info/120457376X

[13] Kraus, Rafaela; Marahrens, Sönke (2019) Künstliche Intelligenz und Innere Führung. S. 276- 294 in: Hartmann, Uwe; Rosen Claus von (Hrsg.) Jahrbuch Innere Führung 2019. Bundeswehr im Aufbruch. Hindernisse von den verteidigungspolitischen Vorstellungen der AfD bis zu den sicherheitspolitischen Meinungen der Zivilgesellschaft. Berlin: Carola Hartmann Miles Verlag

[14] Leonardi, Paul M. (2011) When Flexible Routines Meet Flexible Technologies: Affordance, Constraint, and the Imbrication of Human and Material Agencies. MIS Quarterly, Vol. 35, No. 1, S. 147-167. http://www.jstor.org/stable/23043493

[15] Mayring, Philipp (2003) Qualitative Inhaltsanalyse. Grundlagen und Techniken. Weinheim: Beltz.

[16] Muster, Judith; Büchner, Stefanie; Hoebel, Thomas; Koepp, Tabea (2020) Führung als erfolgreiche Einflussnahme in kritischen Momenten. Grundzüge, Implikationen und Forschungsperspektiven. S. 285- 305 in: Barthel, Christian (Hrsg.) Managementmoden in der Verwaltung. Sinn und Unsinn. https://doi.org/10.1007/978-3-658-26530-4_13

[17] Orlikowski, Wanda J. (2000) Using Technology and Constituting Structures: A Practice Lens for Studying Technology in Organizations. Organization Science 11 (4), 404–428. DOI: 10.1287/orsc.11.4.404.14600.

[18] Posner, Christine (2021) Digitalisierung für die Landes- und Bündnisverteidigung: Die Bundeswehr auf dem Weg zu Big Data Analytics … und was hat das mit Führung zu tun? S. 323 – 340 in: Hartmann, Uwe; Janke, Reinhold; von Rosen, Claus (Hrsg.) Jahrbuch Innere Führung 2021/2022. Ein neues Mindset für Landes- und Bündnisverteidigung. Carola Hartmann Miles-Verlag: Berlin.

[19] Rump, Jutta; Eilers, Silke (2021) Einführung. S. 1-16 in: Rump, Jutta, Eilers, Silke (Hrsg.) Die vierte Dimension der Digitalisierung, IBE-Reihe, https://doi.org/10.1007/978-3-662-59418-6_1

[20] Rumpp, Jutta; Zapp, David; Eilers, Silke (2017) Erfolgsformel: Arbeiten 4.0 und Führung 4.0. Institut für Beschäftigung und Employability, Ludwigshafen. https://www.ibe-ludwigshafen.de/download/arbeitsschwerpunkte-downloads/digitalisierung/Erfolgsformel-Arbeiten-4.0- und-FuCC88hrung-4.0_NEU_2.pdf

[21] Strauss, Anselm; Corbin, Juliet (1996) Grounded Theory: Grundlagen Qualitativer Sozialforschung. Weinheim: Belz.

[22] Thiemann, Daniel (2021) Führen und Entscheiden in modernen Arbeitswelten – Was verändert die Digitalisierung? S. 143-162 in: Kaiser, Stephan; Kozica, Arjan; Böringer, Frank;Wissinger, Josef (Hrsg.) Digitale Arbeitswelt. Wie Unternehmen erfolgreich die digitale Transformation gestalten können. Wiesbaden: Springer Gabler. https://doi.org/10.1007/978-3-658- 33224-2

Affektdynamiken und organisationale Unruhe. Sozialität und Emotionalität des Technologie-Transfers in Sozial-Unternehmen

Alexander Degel*, Katharina Liebsch
Fak. Für Geistes- und Sozialwissenschaften
Arbeitsbereich Mikrosoziologie
Helmut-Schmidt-Universität / Universität der Bundeswehr
Hamburg
*liebschk@hsu-hh.de

Antje Masemann*, Eric Sons
Abteilung Soziale Arbeit
Northern Business School
Hamburg
*antje.masemann@nbs-hochschule.de

***Kurzfassung* – Digitalisierung von Arbeitsabläufen und organisationaler Kommunikation vollzieht sich im Rahmen eines kulturellen Aushandlungsprozesses, an dem Technik, Leitung und Mitarbeitende gleichermaßen aktiv sind. Zudem ist die Einführung digitaltechnischer Neuerungen in Arbeit und Organisation begleitet von sozialen und emotionalen Prozessen, die sich im kollegialen Miteinander, in der sozialen Aushandlung der zeitlichen und strukturellen Gestaltung von Arbeitsabläufen sowie im Kontakt mit Externen, z.B. Kund:innen oder Klient:innen zeigen. Die Einführung neuer digitaler Arbeitsweisen stößt auf Skepsis und Widerstand wie auch auf Neugier und Begeisterung bei den Mitarbeitenden und so sind psychosoziale Abwehr und Idealisierung elementare Aspekte eines jeden Digitalisierungsprozesses.**

Der Beitrag zeigt am Beispiel ausgewählter sozialer Dynamiken in Sozial-Unternehmen, wie die Neu-Strukturierung von Arbeitsabläufen durch Digitalisierung auch Prozesse sozialer und psychischer Ordnungsbildung aktiviert und sich mit diesen verschränkt.

Stichworte – Digitalisierung in Sozialunternehmen, sozio-kulturelle Herstellung von Ordnung, Transfer und Adaption von Technik als Aushandlungsprozess, psycho-organisationale Abwehr

I. Einleitung

Organisationen und Unternehmen der Sozialwirtschaft sind unterschiedlich gut für die Übernahme digitaler Technologien und Arbeitsformen vorbereitet, gerüstet und geeignet [1] [2]. Zwar werden die großen Wohlfahrtsverbände Caritas, Diakonie, DRK-Wohlfahrt und Paritätischer Wohlfahrtsverband seit 2019 durch größere Fördersummen darin unterstützt, ihren Digitalisierungsprozess strategisch anzugehen und über diese Förderung auch entsprechende Stellen oder Abteilungen einzurichten, anderen Einrichtungen hingegen fehlen die Ressourcen für ein konzertiertes, verbandliches Vorgehen in Sachen Digitalisierung. Sie verfügen nur eingeschränkt über zeitliche, personelle und informationelle Ressourcen, die es ermöglichen, passgenaue Lösungen für all solche Anforderungen und Probleme zu erarbeiten, die die Umstellung von analoger zu digitaler Interaktion mit sich bringen. Aber auch die Sozial-Unternehmen, in denen Digitalisierung nur langsam voranschreitet, sind in ihrem Arbeitsalltag damit konfrontiert, dass nicht nur viele soziale und gesellschaftliche Realitäten, sondern auch organisationale Abläufe mittlerweile digital vermittelt sind: von der Software zur Verwaltung von Personaldaten über diverse Formen digitaler Kommunikation und Information bis hin zu auf Algorithmen basierenden diagnostischen Einschätzungen und Interventionsempfehlungen. Damit einher geht die Aufforderung, darauf zu reagieren und sich darauf einzustellen.

Wenn entsprechend Planung und Einführung von organisationalen, personellen und digitaltechnisch-infrastrukturellen Neuerungen initiiert werden, nehmen diese viel Raum ein und binden Zeit und Arbeitskraft. Da aber Sozial-Unternehmen nicht selten am Limit arbeiten, weil sie anhaltend mit existenziellen Fragen und dringlichen Problemen konfrontiert sind, die umgehend Reaktion und Intervention erfordern, ist Digitalisierung im Feld Sozialer Arbeit notwendigerweise ambivalent – einerseits eine weitere, zusätzliche Aufgabe und Herausforderung, andererseits ein Prozess, der auch eine Perspektive auf Verbesserung und Erleichterung von Arbeitsabläufen verspricht.

Wie Organisationen und Einrichtungen der Sozialen Arbeit Prozesse von Digitalisierung konkret auf den Weg bringen und wie sie mit organisationskulturellen Verwerfungen und sozialen und emotionalen Beunruhigungen bei der Etablierung neuer Digital-Technologien umgehen, beschreibt dieser Beitrag. Am Beispiel ausgewählter Befunde und Beobachtungen, die wir im Rahmen ethnografischer Erhebungen in zwei Sozial-Unternehmen in den Jahren 2021 und 2022 gesammelt haben, zeigen wir, wie intersubjektive Aushandlungsprozesse und Psychodynamiken die organisational-kulturelle Ordnung re-organisieren.

Grundlage dieses Beitrags ist eine umfassende Studie zur Digitalisierung psychosozialer Beratungsarbeit, die Theorie generierend angelegt ist und sich an der Grounded Theory [3] [4] orientiert. Dabei beeinflussen sich Erhebung und Auswertung spiralenförmig – bei der Auswertung entstehende Einsichten („Codes“) werden durch weitere Erhebungen vertieft. Dabei entstanden Beobachtungsprotokolle von Teamsitzungen, aus Workshops, Expert:innen-Interviews und

https://doi.org/10.24405/14578

Interviews mit Mitarbeiter:innen sowie eine Fragebogen-Erhebung aller Mitarbeitenden zum Thema Digitalisierung.

II. Digitalisierung als Prozess der Aushandlung und der organisationalen Strukturierung

Die Entscheidung zur Einführung digitaltechnischer Neuerungen in den Arbeitsabläufen von Sozialunternehmen wird formal von der Geschäftsführung beschlossen und verantwortet und von den Mitarbeitenden mitgetragen. Dahinter aber stehen komplexe Aushandlungen zwischen allen Beteiligten, die nicht nur verschiedene Interaktionssituationen samt unterschiedlicher Verhandlungsstrategien umfassen, sondern auch von den situativ-lokalen Verhandlungssettings und strukturellen Kontexten bestimmt sind – beispielsweise davon, ob es in der Organisation einen Betriebsrat gibt oder nicht, ob das Thema Digitalisierung in einen laufenden Organisationsentwicklungsprozess eingebettet ist, wieviel finanzielle Mittel und zeitliche Ressourcen für die Einführung digitaler Technik zur Verfügung stehen und manchmal auch davon, ob überhaupt ein tragfähiges Netzwerkkabel vorhanden ist. Digitalisierung führt also nicht nur eine technisch-infrastrukturelle Ordnung ein, die als „Skript" [5] sowohl die Erwartungen und Normativitäten von Technik-Designprozessen transportiert als auch die Verhaltensweisen der Nutzenden lenkt und sie dazu auffordert, „bestimmte Voraussetzungen für das Verhalten […zu] erzeugen" [6]. Digitalisierung setzt darüber hinaus auch die soziale Produktion einer neuen „negotiated order" in Gange [7, 8]. Diese zeigt sich in der zuweilen von externen Beraterfirmen angestoßenen Veränderungen sozialer Interaktionsbeziehungen, dem Entstehen neuer sozialer Gruppen innerhalb der Organisation und neuer Bedeutungen, die das Selbstverständnis der Organisation in Frage stellen und verändern [9]. Das Beispiel eines achtmonatigen Einführungsprozesses von Kalendersoftware in einem Sozialunternehmen mit Beratungsschwerpunkt soll diese Dynamiken veranschaulichen.

A. *Das Miteinander neu erfinden*

In dem Beratungszentrum wurde eine bereits genutzte Kalendersoftware durch eine andere ersetzt. Der Umgang mit einem digitalen Medium zur Terminplanung und -koordination war also nichts grundlegend Neues für die Mitarbeitenden. Der Wechsel wurde initiiert, da die zuvor genutzte Software als unübersichtlich und unzuverlässig empfunden wurde. Auch sollte perspektivisch eine Online-Terminvergabe für Klient:innen eingeführt werden, was mit der bis dato eingesetzten Software nicht umsetzbar war. Mit der Entscheidung, eine alternative Kalendersoftware einzuführen, folgte die Organisation der Empfehlung einer externen IT-Beratungsfirma. Dieser Empfehlung waren workflow-Analysen und die Perspektivierung notwendiger Veränderungen vorangegangen, die im Rahmen einer kurzen Einheit zur Organisationsentwicklung mit einer weiteren externen Firma entwickelt wurden. Dabei stand das Thema Digitalisierung ganz oben auf der Agenda.

Die Einführung der neuen Kalendersoftware wurde zunächst durch den externen IT-Dienstleister begleitet und der Umgang damit in Kleingruppen erprobt. Dabei wurde schnell deutlich, dass die etablierten Arbeitsroutinen in der Beratungsstelle nicht zu der von der Software des neuen Kalenders vorgesehenen Bedienung passten. Es gab viele Detailfragen zur Nutzung, großen Bedarf an individueller Beratung und Unklarheiten strukturelle Funktionsweisen betreffend, die von der IT-Beratungsfirma nur punktuell und sporadisch geklärt wurden. Daraufhin wurde die Zusammenarbeit mit der Firma aufgekündigt und das Team entwickelte und erarbeitete Zugänge zur Problemlösung nun eigenständig.

Dies umfasste beispielsweise die Etablierung einer Gruppe von „Super-User", die Fragen der Kolleg:innen beantworteten und sie beim Üben und in der Anwendung der neuen Software anleiteten. Die Gruppe der Super-User bestand aus sechs Mitarbeitenden, die sich wöchentlich über einen Zeitraum von sechs Monaten für 90 Minuten trafen, die Erfahrungen mit der neuen Software reflektierten und Neuregelungen und Umgestaltungen für eine reibungslose Integration anregten. Dementsprechend wurden Arbeitsabläufe verändert und ein Arbeitsbereich so umgestaltet, dass er als Schnittstelle von Klient:innen und Mitarbeitenden fungiert. Dieser Bereich erhielt neue Arbeitsplatzbeschreibungen, die es den Mitarbeitenden abverlangten, die veränderte Arbeitsorganisation und die neuen digitalisierten Abläufe konstruktiv umzusetzen. Um den dabei auftretenden Irritationen und Anstrengungen und subjektiven Bewältigungsstrategien von beispielsweise Vermeidung oder Delegation von Arbeitsaufgaben zu begegnen, wurden sogenannte „Optimierungstreffen", eingeführt, bei denen die Mitarbeitenden gezielte und problemorientierte Schulungen zum Umgang mit der Kalendersoftware erhielten. Arbeitsroutinen und Bedarfe der Mitarbeitenden wurden analysiert, um daraus Standards für die Arbeit mit dem neuen Kalender wie auch eine klare Systematisierung verschiedener Typen der Terminvergaben zu erarbeiten. Des Weiteren wurden die personelle und kollegiale Passung von Arbeitsteams überprüft und Umstrukturierungen angeregt.

B. *Situationen und Strategien*

Bereits diese kurze Beschreibung der Veränderungsdynamiken, die mit der Einführung einer einzigen neuen Software verbunden waren, macht die Bedeutung des sozialen und kulturellen Settings von Digitalisierung sichtbar. Zentral ist, ob und wie es gelingt, den Austausch von Informationen zu organisieren. Dafür ist es erforderlich, Informationsregulation durch die neue Software an Fragen, Bedarfe und Irritationen der Mitarbeitenden anzukoppeln. Es braucht Informationsvermittler:innen, die sowohl die Technik verstehen und sie souverän bedienen können als auch die Probleme und Schwierigkeiten von Kolleg:innen kennen und bereit sind, sich ihnen unterstützend zuzuwenden. Die im Zuge dessen aktivierten bzw. neu geschaffenen Strategien einer konstruktiven Aushandlung und Bewältigung der mit der Einführung von Digitaltechnik verbundenen Unterbrechung von Arbeitsroutinen, sozialen Spannungen und kollegialen Verwerfungen, individuellen Verunsicherungen und Blockaden sind vielfältig. Allein unser kleines Veranschaulichungsbeispiel zeigt, dass die Integration von neuer Digitaltechnik die Organisation und ihre Mitarbeitenden in Bewegung bringt, unterschiedliche externe Akteure an die Organisation ankoppelt und wieder löst, und Aushandlungsprozesse auf mehreren Ebenen und mit verschiedenen Aktivitäten in Gange bringt.

Aushandlungsstrategien müssen dabei die intersubjektive Interaktion wie auch die Mensch-Technik-Interaktion adressieren, mikropolitisches Konfliktmanagement realisieren, Lenkung und Steuerung von Organisationsentwicklungsprozessen sowie umfassende

Informationspolitik betreiben. Dazu braucht es neben dem kreativen „work-around“ im Umgang aller mit der neuen Technik kollegiale und strategische Regiekonzepte, umfassende und transparente organisationsinterne Kommunikation, die Bereitschaft aller zu Flexibilität und Veränderung wie auch die Dokumentation, Reflexion und Bilanzierung der vollzogenen Veränderungen und deren soziale und organisationale Anerkennung.

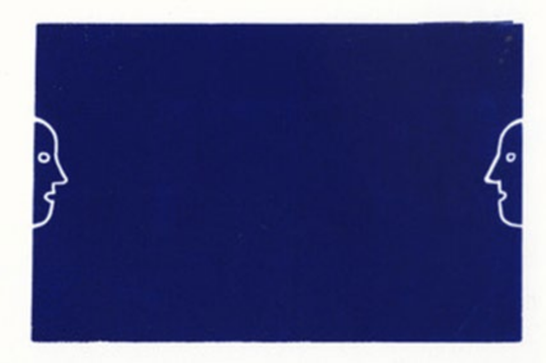


ABBILDUNG 1: „TALKING HEADS“.

III. DIGITALISIERUNG ALS PSYCHO-SOZIALE DYNAMIK

Die Einführung digitaler Technik in Organisationen und Unternehmen betrifft nicht nur Prozesse der Arbeitsorganisation, sondern berührt auch den Umgang mit Affekten innerhalb der Organisation [10, 11, 12, 13], wie der Psychoanalytiker und Organisationsforscher Anton Obholzer erläutert: „The assumption is that there is anxiety specific to and arising from the nature of the work and that the institution defends itself against this anxiety in such a way that the emphasis of the structure is on defence-related rather than work-related functioning. If this is correct, then it is important for managers to realize that any attempt to alter the specific way in which work is organized in their institution must, by definition, mean a disruption of the anxiety-holding system, with a consequent release into the structure of anxiety and resistance to change” [14].

Im Feld der Sozialen Arbeit beispielsweise spielen negative und belastende Affekte aufgrund der Arbeit mit Klient:innen, die sich in prekären Lebenslagen befinden und zumeist bedürftig sind, eine Rolle. Es gehört zu den Aufgaben von Sozial-Unternehmen, die Mitarbeitenden vor den Ängsten und Konflikten zu schützen, die aus der Arbeit heraus entstehen. Auch müssen Sozial-Unternehmen die Bearbeitung und Bewältigung solcher Affekte sicherstellen, um arbeitsfähig zu bleiben. Dies wird u.a. durch klare Strukturen, nachvollziehbare Prozesse und einen offenen Umgang gewährleistet [15]. Fehlen solche Strukturen und Strategien oder verändern sie sich, werden kollektiv-institutionelle Abwehrmechanismen aktiviert, um Unsicherheit und Angst in Schach zu halten.

Aus dieser Perspektive betrachtet, bringen auch die mit organisationalen Digitalisierungsprozessen verbundenen Anforderungen und Neuerungen die psychische Struktur der Mitarbeitenden in Bewegung. Beispielsweise verändert Digitalisierung das Verhältnis von Anwesenheit und Abwesenheit: Während der Face-to-Face-Kontakt mit Klient:innen seltener stattfindet und deren physische Präsenz aufgrund der Zunahme von Online-Kommunikation abnimmt, ziehen die Klient:innen mit der Video-Beratung im Home-Office nun auch ins private Zuhause der Berater:innen ein oder unterbrechen deren Nachtruhe, wenn sie um drei Uhr morgens Text-Messages per Social Media schicken. Damit werden Grenzen verschoben – zwischen Innen und Außen, zwischen Arbeit und Privatleben bzw. Freizeit, zwischen Zugehörigkeit und Verantwortung. Solche Entgrenzungen können gefestigte psychosoziale Abwehrmechanismen von Projektion und Spaltung bzw. die Art und Weise verändern, wie Angst, Wut und Hass abgespalten und nach außen projiziert werden. Eine mögliche Folge ist die Erhöhung von Angst bei den Mitarbeitenden, es entladen sich destruktive Affekte und es kommt zu einem Anstieg paranoider Fantasien und Ängsten vor Fragmentierung. So gesehen, stellen die Digitalisierungsinitiativen eine Herausforderung für das Funktionieren einer Organisation dar.

A. Neuerungen zwischen Idealisierung und Abwehr

Bei einem freien Träger im Bereich der Jugendhilfe, der ein breites Spektrum an ambulanten und stationären Aktivitäten anbietet, machte die im Vorfeld durchgeführte Befragung aller Mitarbeitenden deutlich, dass eine große Mehrheit mit Digitalisierung Hoffnungen auf mehr Effizienz und Effektivität, Transparenz und Sicherheit verband und diese als eine positive Entwicklung ansah. Während zu Beginn der 2000er Jahre die sozialpolitischen Anforderungen des New Public Management samt der damit verbundenen Umstrukturierungen im Bereich der Sozialen Arbeit noch auf breiten Widerstand stießen und als neoliberale Tendenz der Vermarktlichung des Sozialen zurück gewiesen wurden [17, 18], trifft der gesellschaftliche Megatrend Digitalisierung im Bereich der Sozialarbeit heute auf deutlich weniger Kritik [18]. Unsere Fragebogen-Erhebungen, Beobachtungen und Interviews zum Digitalisierungsprozess ausgewählter Sozial-Unternehmen dokumentierten Skepsis und Kritik lediglich beim Thema Datenschutz. Ansonsten überwogen Aufgeschlossenheit, Neugier und ein breiter und eher diffuser positiver Erwartungshorizont. Artikuliert wurde die Hoffnung, dass Digitalisierung Kommunikation vereinfache, Zugänge zu Ziel- und Klient:innen-Gruppen vergrößere, Bürokratie abbaue, Verfahrenswege sichtbar mache und Transparenz schaffe. Die Perspektive auf vom Arbeitgeber bereit gestellte Technik („Diensthandy“) und die Einstellung eine:r „Digitalisierungsbeauftragten“ beflügelte die Hoffnung auf Erleichterung der alltäglichen Arbeit und Verbesserung von Kooperation und Führung.

Die Befragten nutzten die Perspektive der digitalen Umgestaltung organisationaler Kommunikations- und Arbeitsroutinen für die Artikulation von sowohl Kritik an strukturellen Unklarheiten und Lücken als auch Wünschen nach Veränderungen im kollegialen Miteinander und mit der Leitung. Digitalisierung fungierte hier als Horizont der organisationalen Selbstverständigung. Sie diente der Problematisierung verfestigter Strukturen und stellte eine Art „Wunschmaschine“ [19] dar. Dabei wurden aber auch Unsicherheiten, Affekte reichend von Wut, Verzweiflung, Scham und Aggression und organisationale Abwehrmechanismen sichtbar.

B. Spaltung, Delegation und Projektion

Die Breite und Vielfalt der Aufgaben und Tätigkeitsbereiche der Organisation wurden von den Mitarbeitenden nicht als Stärke empfunden. Sie wussten zum Teil wenig über die Organisation als Ganzes, in der sie tätig waren. Viele kannten nur ihr Team sowie die einzelnen Projekte ihres Bereichs, und auch das war nicht bei allen Mitarbeitenden gegeben. *„Von außen wirkt der Träger* *lebendig und kreativ, aber in der Innenperspektive ist das nicht so, es gibt kein richtiges Kennenlernen. Es fehlt das Interesse an und die Zeit für Vernetzung"*, berichteten Führungskräfte und es gab nur wenig Erfolge, Barrieren des Austauschs und die Separierung der Arbeitsfelder und Teams abzuschwächen. Weil organisationales Wissen nicht für alle verfügbar war, kam es vor, dass die Zusammenarbeit mit anderen Organisationen gesucht wurde, obwohl der eigene Träger über passende Angebote verfügte. Manchmal gab es in der Organisation keine Kenntnis davon, dass Initiativen für identische Zielgruppen doppelt angeboten wurden: *„Wir haben erst nach einem Jahr gesehen, dass es parallel zwei Nähprojekte in unserer Organisation gibt, die nichts voneinander wussten"*, erzählte eine Mitarbeiterin. In der Organisationsstruktur manifestierte sich diese Separierung im Organigramm. Dieses *„wirkt durcheinander, unübersichtlich und scheint veraltet"*. Auch zeigte sie sich in der Webpage der Einrichtung, deren Neustrukturierung ein Ziel im Rahmen der Digitalisierungsbestrebungen der Organisation darstellte.

Die Separierung der Arbeitsbereiche und fehlender Austausch untereinander führten auch dazu, dass Unzufriedenheit und Affekte an die Führungskräfte delegiert und nur selten im Team bearbeitet wurden. So sagte eine Mitarbeiter:in: *„Bei uns gibt es eine Eskalationsspirale nach oben. Wenn etwas in den Teams nicht läuft, ist immer die Führungskraft schuld. Die bekommen dann die ganze Aggression ab"*.

In aller Regel ist die Arbeit von Organisationen so strukturiert, dass Vorgesetzte Arbeit an Mitarbeiter:innen delegieren und sie mit der Verantwortung für die Umsetzung betrauen. In der von uns untersuchten Organisation aber verrichteten Führungskräfte nicht selten Aufgaben von Mitarbeiter:innen. Das führte dazu, dass sehr gut ausgebildete Sozial Arbeiter:innen viele Freiheiten und Verantwortung in der Arbeit mit Klient:innen hatten, aber innerhalb der Organisation sehr wenig Verantwortung übernahmen. Dies wurde zusätzlich unterstützt durch Regelungen zur Arbeitsteilung, die mit der Eindämmung von Kosten begründet wurden. So sollten Serviceanfragen an den externen IT-Dienstleister erst von den Führungskräften genehmigt werden. Wenn Mitarbeiter:innen beispielsweise Probleme beim Drucker oder der Einrichtung von IT-Geräten hatten und dafür Hilfe brauchten, musste dies *„erst über den Schreibtisch der Führungskraft und genehmigt werden, weil die enorm teuer sind"*. Umgekehrt aber wurden konkrete Umsetzungsarbeiten durchaus an „teure" Führungskräfte delegiert. Dann übernahmen Führungskräfte die Einrichtung der Laptops für neue Mitarbeiter:innen und führten auch andere einfache Tätigkeiten an Stelle derer aus. Im Ergebnis schwächte dies die Eigenverantwortung der Mitarbeitenden und führte zudem dazu, dass die Leitungen kaum mehr Zeit für strategische oder personelle Aufgaben hatten. Die ohnehin überarbeiteten Führungskräfte akzeptierten diese Delegationen, um sich vor Kritik und Aggression der Mitarbeitenden zu schützen. So schildert ein:e Vorgesetzte:r: *„Wenn ein Mitarbeiter mich fragt, ob ich das übernehme, fällt es mir schwer nein zu sagen. Ich denke viele Führungskräfte vermeiden da einen Konflikt, aus Sorge, da nicht demokratisch zu wirken, dass man dann autoritär wirkt, sich über die anderen erhebt"*.

Entsprechend zögerlich wurden in dem Unternehmen Entscheidungen getroffen. Eine latente Angst vor Beschämung trug dazu bei, Entscheidungen zu verzögern und zu vermeiden oder an externe Dienstleister zu delegieren. Als ein Mitarbeiter die Idee einbrachte, ein neues Logo für die Organisation zu gestalten, zirkulierte diese Anregung in der Organisation und es wurde ein weiterer, sechs Wochen entfernter Termin vereinbart. Andere Aufgaben, wie die angestrebte Neuorganisation des E-Mail-Verteilers samt der Vorgabe eines E-Mail-Betreff-Schemas, das die Kommunikation vereinheitlichen soll, blieben liegen. Die Furcht vor negativen Reaktionen und Abwertung war groß – in der Formulierung einer Mitarbeiter:in: *„Wir haben nur einen Versuch"*.

Deshalb wurden in dem Unternehmen Entscheidungen sehr gut vorbereitet und sich darum bemüht, alle möglicherweise Betroffenen miteinzubeziehen. Dies bewirkte, dass Veränderungsinitiativen ihren anfänglichen Schwung verloren und dann nicht selten im Sande verliefen.

C. Mechanismen und Muster psychosozialer Abwehr als Blockade von Veränderung

Im Zuge der Digitalisierung von Arbeit und Organisation verbinden Mitarbeitende ihre individuelle psychische Struktur unter dem Einfluss organisationaler Gruppenphänomene und struktureller Bedingungen zu einer kollektiven Gefühlslage innerhalb der Organisation [20]. Mit den dabei entstehenden Affekten muss die Organisation so umgehen, dass das unbewusste und erlebte Angstlevel gering gehalten wird. Dazu kann die Leitung stellvertretend für die Mitarbeitenden diese Spannungen, Affekte und Ängste wahrnehmen, aufnehmen, verarbeiten und diese dann in einem gleichermaßen stellvertretenden Prozess in verarbeiteter Form wieder an den Mitarbeiter:innen zurückgeben. Gelingt dies aufgrund von unklarer Führung oder diffusen Strukturen und Abläufen nicht, steigen Unsicherheit und Angst in der Organisation und es werden psychosoziale Abwehrmechanismen aktiviert, die helfen, diese Ängste auf organisationaler Ebene abzuwehren [21, 22, 23]. Diese reichen von Bagatellisierung, Dramatisierung, Idealisierung, Rationalisierung und Sublimierung bis hin zur Spaltung, Projektion und projektiver Identifikation, Entwertung und Idealisierung in Form von Heilserwartungen [24]. Schon vor mehreren Jahrzehnten hatte der Psychoanalytiker Wilfred Ruprecht Bion [25] Muster psychosozialer Abwehr in Gruppen herausgearbeitet: Im *Kampf-Flucht Muster* werden alle Teilnehmenden eines Teams in Auseinandersetzungen verstrickt, Ideen werden sofort in Frage gestellt, jeder kann im Verlauf der Diskussion zum Gegner werden. Beim *Muster der Abhängigkeit* wird formellen oder informellen Leiter:innen blind gefolgt. Das *Muster der Paarbildung* bringt zwei eingeschworene Partner hervor, die scheinbar die Lösung für alle Probleme kennen. Derartige Mechanismen und Muster der Abwehr sind unbewusst und funktional für die Kontrolle von Ängsten. Aber sie sorgen auch dafür, dass die Organisation tendenziell veränderungsresistent bleibt. Entsprechend können sich auch die Effekte und Wirkungen von Digitalisierung nur eingeschränkt entfalten.

Insgesamt zeigt sich: Digitalisierungsprozesse bzw. die Einführung neuer digitaler Technologien sind begleitet von Affektdynamiken. Diese bewirken organisationale Unruhe, weil sie Umstrukturierungen erforderlich machen und Aushandlungsanstrengungen erzeugen. Die Einführung neuer digitaler Technologien stellt neben den Arbeitsabläufen und der psychischen Struktur der Mitarbeitenden auch die Organisationskultur von Sozialunternehmen in Frage. Dies ruft weitere affektive Abwehrbewegungen hervor, die innovative Prozesse blockieren können. Die Erforschung dieser multidimensionalen Prozesse und ihren Risiken und Chancen bringt nicht nur für die sozialarbeiterische Praxis wichtige Einsichten mit sich. Sie leuchtet auch einen blinden Fleck interdisziplinärer Digitalisierungsforschung aus.

DANKSAGUNG

Die Autoren bedanken sich für die Förderung bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr [Projekt PsyBeDig].

LITERATURVERZEICHNIS

[1] BMFSFJ, „Digitale Agenda für eine lebenswerte Gesellschaft.,“ 2019. [Online]. Available: https://www.bmfsfj.de/blob/121676/d7e37de51edd87025f3e2f61698a82c3/digitale-agenda-fuer-eine-lebenswerte-gesellschaft-data.pdf. [Zugriff am 26. August 2022].

[2] Bundesarbeitsgemeinschaft der Freien Wohlfahrtspflege , „Organisationsentwicklung der freien Wohlfahrtspflege unter den Vorzeichen der Digitalisierung,“ 2017. [Online]. Available: https://www.bagfw.de/veroeffentlichungen/stellungnahmen/positionen/detail/digitale-transformation-und-gesellschaftlicher-zusammenhalt-organisationsentwicklung-der-freien-wohlfahrtspflege-unter-den-vorzeichen-der-digitalisierung. [Zugriff am 26 August 2022].

[3] B. G. Glaser und A. L. Strauss, The Discovery of Grounded Theory, New York: Aldine Publ., 1967.

[4] A. L. Strauss, Qualitative Analysis for Social Scientists, Cambridge: MIT University Press, 1987.

[5] M. Akrich, „The De-scription of Technical Objects,“ in *Shaping Technology/Building Society*, Cambridge, MIT Press, 1997, pp. 205-224.

[6] I. Schulz-Schaeffer, „Akteur-Netzwerk-Theorie: Zur Koevolution von Gesellschaft, Natur und Technik,“ in *Soziale Netzwerke : Konzepte und Methoden der sozialwissenschaftlichen Netzwerkforschung*, München, Oldenbourg, 2000, pp. 187-210.

[7] G. A. Fine, „Negotiated Orders and Organizational Cultures,“ *Annual review of sociology,* Nr. 1, pp. 239-262, 1984.

[8] E. Nadai und C. Maeder, „Negotiations at all Points? Interaction and Organization,“ *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research,* Bd. 1, Nr. 9, 2007.

[9] S. Ranson, B. Hinings und R. Greenwood, „The Structuring of Organizational Structures,“ *Administrative science quarterly,* Nr. 1, pp. 1-17, 1980.

[10] P. Fürstenau, „Psychoanalytisch-systemische Teamsupervision im psychiatrisch-psychosomatischen Bereich zwecks Förderung der Teamentwicklung,“ in *Formen der Supervision. Supervisionskonzepte und Praxis im Klinikkontext*, Frankfurt am Main, Verlag für Akademische Schriften, 1998, pp. 71-82.

[11] B. Sievers, D. Ohlmeier, B. Oberhoff und U. Beumer, Das Unbewusste in Organisationen, Gießen: Psychosozial-Verlag, 2003.

[12] R. Haubl, R. Heltzel und M. Barthel-Rösing, Gruppenanalytische Supervision und Organisationsberatung, Gießen: Psychosozial-Verlag, 2005.

[13] T. Giernalczyk und M. Lohmer, Das Unbewusste im Unternehmen. Psychodynamik von Führung, Beratung und Change Management, Stuttgart: Schäffer-Poeschel, 2012.

[14] A. Obholzer, „Managing the unconscious at work,“ in *Group Relations, Management, and Organization*, Oxford, Oxford University Press, 1999, pp. 87-97.

[15] T. Giernalczyk und H. Möller, Entwicklungsraum – Psychodynamische Beratung, Göttingen: Vandenhoeck & Ruprecht, 2018.

[16] C. Butterwegge, „Neoliberale Modernisierung, Sozialstaatsentwicklung und Soziale Arbeit,“ in *„Modernisierungen" methodischen Handelns in der Sozialen Arbeit*, Wiesbaden, VS Verlag, 2010, pp. 49-88.

[17] R. Sorg, „Kapitalismus und Soziale Arbeit,“ *Utopie Kreativ,* Nr. 194, pp. 1096-1108, 2006.

[18] S. Zuboff, The Age of Surveillance Capitalism: The Fight for the Future at the New Frontier of Power, London: Profile Books, 2019.

[19] G. Deleuze und F. Guattari, Tausend Plateaus. Kapitalismus und Schizophrenie II, Berlin: Suhrkamp, 1992.

[20] M. Lohmer und M. Möller, Psychoanalyse in Organisationen. Einführung in die psychodynamische Organisationsberatung, Stuttgart: Kohlhammer, 2019.

[21] E. Jaques, „Social Systems as a Defence against Persecutory and Depressive Anxiety: A Contribution to the Psycho-Analytical Study of Social Processes,“ in *New Directions in Psycho-Analysis: The Significance of Infant Conflict in the Pattern of Adult Behaviour*, London, Tavistock, 1955, pp. 478-498.

[22] I. Menzies Lyth, „A Case-Study in the Functioning of Social Systems as a Defence against Anxiety. A Report on a Study of the Nursing Service of a General Hospital,“ *Human Relations,* Bd. 2, Nr. 13, pp. 95-121, 1960.

[23] L. Hirschhorn, The Workplace within: Psychodynamics of Organisational Life., Cambridge, London: The MIT Press, 1988.

[24] T. Giernalczyk und H. Möller, Entwicklungsraum – Psychodynamische Beratung, Göttingen: Vandenhoeck & Ruprecht, 2018.

[25] W. R. Bion, Erfahrungen in Gruppen und andere Schriften, Frankfurt am Main: Suhrkamp, 1961.

Spannungsfelder und Erfolgsfaktoren kommunaler Digitalisierung: Erste Ergebnisse der Einführung des digitalen Bauantragsverfahrens in Ludwigsburg

Thomas Kuder*, Bastian Manteuffel**
vhw – Bundesverband Wohnen und Stadtentwicklung
Berlin, Deutschland
*tkuder@vhw.de
**bmanteuffel@vhw.de

Gary S. Schaal, Christina Schaefer, Sebastian Dumm
Fakultät für Wirtschafts- und Sozialwissenschaften/Helmut-Schmidt-Universität
Hamburg, Deutschland

Thomas Perry, Gero Serfas
Q Agentur für Forschung
Mannheim, Deutschland

***Kurzfassung* – Das 2017 verabschiedete Onlinezugangsgesetz (OZG) setzt v.a. Kommunalverwaltungen unter Druck, ihre Verwaltungsleistungen möglichst schnell digital verfügbar und bearbeitbar zu machen. Je nach „Digitalisierungstiefe" erfordert die spezifische Räumlichkeit und Zeitlichkeit digitaler Infrastrukturen allerdings nicht nur technische Lösungen. Zentral für den Erfolg bei der Umsetzung des OZG sind daher *Governance-Konstellationen*. Der Aufsatz rekonstruiert empirisch die unterstützenden und hemmenden Governance-Konstellationen für den Prozess der Digitalisierung des Bauantragsverfahrens auf kommunaler Ebene in Baden-Württemberg und identifiziert theoriegeleitet zentrale Spannungsfelder kommunaler Digitalisierung.**

Stichworte – Onlinezugangsgesetz, Verwaltungsdigitalisierung, (Mehrebenen-)Governance

NOMENKLATUR

OZG	Onlinezugangsgesetz
IV##	Interview ID
FITKO	Föderale IT-Kooperation
LeiKa	Leistungskatalog der öffentlichen Verwaltung

I. EINLEITUNG

Die Entwicklung digitaler Technologien ermöglicht das Imaginieren unterschiedlichster Anwendungsfelder in Städten. ‚Intelligente' Verkehrssteuerungssysteme, digitale Kommunikation mit BürgerInnen oder Sensorik im Stadtraum und daraus resultierende Datenmengen, die das Verwalten und Regieren der Bevölkerung effizienter, effektiver oder gar ‚evidenzbasierter' gestalten sollen. Neben diesen vielfältigen Schnittstellen zum Thema Digitalisierung, welche Kommunen in Deutschland potenziell betreffen, sind Kommunen durch das 2017 verabschiedete Onlinezugangsgesetz (OZG) vor allem als Verwaltungen angesprochen, sich mit dem Thema auseinanderzusetzen. Je nach „Digitalisierungstiefe" [1, p. 11] erfordert die spezifische Räumlichkeit und Zeitlichkeit digitaler Infrastrukturen nicht nur technische Lösungen. Vor dem Hintergrund historisch gewachsener Ressortstrukturen in Verwaltungen, identifiziert eine Erhebung der Hans-Böckler-Stiftung [1, p. 33] entsprechend das Feld der „Governance und Kollaboration" als drittgrößte Herausforderung, mit der sich Bürgerämter in Deutschland beim Thema der Verwaltungsdigitalisierung konfrontiert sehen. Zum einen mit Blick auf die vertikale Einbettung innerhalb eines politischen Mehrebenensystems [2] [3, p. 6], welches bundes- und landesspezifische Anforderungen an Kommunen stellt, von diesen aber aufgrund unklarer Zuständigkeiten als wenig koordinierend oder unterstützend wahrgenommen werden (IV17:75-76 „keine ordnende strukturierende Hand", IV19:70 „abgespeist"). Zum anderen mit Blick auf die reale Ausgestaltung vor Ort, welche durch eine interne Differenzierung der Verwaltungsstruktur geprägt wird und dadurch, wie sich horizontale Abhängigkeiten mit anderen Behörden und Stakeholdern darstellen. Entsprechend gestalten die lokalspezifischen und historisch gewachsenen (digitalen) Infrastrukturen zur Bearbeitung von Verwaltungsprozessen, aber auch Verwaltungsstrukturen und -zuständigkeiten mit, wie Digitalisierung vor Ort Ausdruck finden und überhaupt bearbeitbar werden kann.

Ferner sind Städte nicht ‚nur' Verwaltungen und haben teilweise weitergehende Ansprüche, Digitalisierung auszugestalten. Digitalisierungsprojekte sind entsprechend lokal sehr unterschiedlich und deren Umsetzungsqualität hängt auch davon ab, welche Akteurskonstellationen sich dem Thema annehmen, wie und ob Budgets freigegeben werden, und welche Motivationen oder strategischen Orientierungen, explizit oder implizit, vorliegen. Digitalisierungsprojekte seien lokal häufig abhängig von sporadischen Präferenzen und Entscheidungen einzelner Personen auf Führungs- oder Entscheidungsebene, während eine tragfähige Koalition der Befürworterschaft häufig fehle [3, p. 6].

Kommunale Digitalisierung ist mehr als die Überführung analoger Daten und Prozesse in die digitale Domäne. Digitalisierung besitzt einen ideativen Überschuss, d.h. der Prozess ist ideen-, wert und prinzipiengeleitet. Er inkludiert – empirisch in unterschiedlicher Intensität – eine Vision des Digitalen, die notwendig vernetzt und sphären- sowie domänenübergreifend ist. Zudem ist Digitalisierung nicht nur Technologie, sondern auch Interaktion und zwar zwischen den NutzerInnen und der digitalen Technologie. Es bilden sich sozio-technologische Systeme aus, deren Erfolg auch von den Einstellungen und Motivationen der Nutzer*innen abhängig ist. Deshalb verfolgt unser Projekt einen interdisziplinären

https://doi.org/10.24405/14579

Ansatz. Es nutzt den Nukleus einer Case Study – die Analyse der Implementation des digitalen Bauantrages im Zuge der Einführung des Digitalen Bauamtes in Ludwigsburg im Kontext des OZG – und ergänzt diese „Tiefenbohrungen“ um weitere Transformationsfälle, die empirisch und über Desk Research erschlossen werden. Der vorliegende Aufsatz fokussiert vor dem skizzierten Hintergrund auf ein Projektziel: unterschiedliche Governance-Konstellationen zu beschreiben, mittels derer unterschiedliche kommunale ‚Digitalisierungen‘ produziert wurden. Konkreter sollen unterschiedliche Strukturmerkmale und Akteurskonstellationen als „Erfolgsfaktoren“ beschrieben werden (Abs. V, B). In Vorbereitung dieser Analyse identifizieren wir zuvor prototypische Spannungsfelder, die u.a. den situativen, institutionellen, rechtlichen Kontext kommunaler Digitalisierungsprozesse darstellen und ihren Erfolg systematisch beeinflussen (Abs. V, A). Grundlage hierfür ist ein interdisziplinärer mixed methods Forschungsansatz (Abs. II). Weitere Informationen zu den Teilprojekten des Konsortialpartners vhw Bundesverband Wohnen und Stadtentwicklung findet sich unter [4].

II. Theorie und Methodik

Das Forschungsprojekt verfolgt einen interdisziplinären Theorieansatz, der empirisch mit einem mixed methods Approach umgesetzt wird.

A. Governance

In der Literatur findet sich die Position, dass die Ausgestaltung der (Mehrebenen-)Governance starken Einfluss auf die Qualität der Umsetzung von kommunalen Digitalisierungsstrategien besitzt [2] [3]. Dieser Spur folgen wir im Projekt und „schneiden“ hierfür mehrere Governancekonzepte zu einem analytischen Tool.

Das Konzept der „Governance“ umfasst den Versuch einer „realitätsgerechter[en]“ Beschreibung einer kontingenten politischen Wirklichkeit [5, p. 7], in welcher eine Vielzahl von staatlichen und nicht-staatlichen Akteuren bei der Aushandlung sozialer Probleme involviert sind [6, pp. 15-16]. In normativer Wendung setzt es einen Rahmen für eine ‚angemessenere‘ Form des Regierens dieser inhärenten Vielfältigkeit sozialer Probleme. Nach Mayntz bedeutet ‚Governance‘ weniger ‚Steuern‘ als vielmehr die analytische Sensibilität für die „wie auch immer zustande gekommene Regelungsstruktur und ihre Wirkung auf das Handeln der ihr unterworfenen Akteure“ [5, p. 5]. Damit impliziert Governance stets eine „Doppelnatur“ aus Prozess zur Herstellung von Regelsystemen sowie ihrer ermöglichenden oder einschränkenden Wirkung auf Handeln. Als Orientierung dient dabei zum einen der von Mayntz & Scharpf vorgestellte Akteurszentrierte Institutionalismus [7], um die vorliegenden Aktivitäten als Akteurskonstellationen zu beschreiben. Diese gehen aus einem spezifischen institutionellen Kontext hervor, welcher bestimmte und nicht andere Interaktionsformen ermöglicht.

Zum anderen sollen in Anlehnung an Jan Kooiman [6] punktuell unterschiedliche Governance-Ebenen identifiziert und ihr Zusammenspiel in den Blick genommen werden. Sie beschreiben unterschiedliche qualitative Bearbeitungsebenen, auf denen ein bestimmtes Thema bzw. die Adressierung eines gesellschaftlichen Problems ihren Ausdruck finden. In der Praxis lassen sich die Ebenen nicht immer klar voneinander trennen, sie können aber einen Orientierungsrahmen bilden, um die vorliegenden Aktivitäten einzuordnen.

1) First Order Governance

Nach Kooiman umfasst die erste Governance-Ebene das Zusammenspiel verschiedener Akteure, um ein spezifisches Problem auf einer alltäglichen Basis zu bearbeiten [6, p. 135]. Die Qualität der Bearbeitung wird mitgestaltet durch den institutionellen Rahmen, innerhalb dessen diese stattfindet. Mit anderen Worten, auf der ersten Governance-Ebene werden institutionelle Regelungen der zweiten Ebene „angewandt“ [8, p. 20], um ein Problem zu identifizieren, abzugrenzen und zu adressieren. Die Definition bei Kooiman ist sehr allgemein, sodass First Order Governance in der Planungsliteratur auch als Umsetzungsebene bzw. „Durchführungsplanung“ verstanden wurde [9].

2) Second Order Governance

Die zentralen Elemente der zweiten Governance-Ebene bilden Institutionen, also Systeme von Regeln, Gesetzen, Rechten, Normen, Organisationen, Überzeugungen und Rollen. Die Liste ließe sich weiterführen, entscheidend ist: Sie setzen den institutionellen Rahmen, innerhalb dessen Governance-Aktivitäten auf der ersten Ebene stattfinden können.

3) Meta-Governance (Third Order)

Die dritte Governance-Ebene umfasst Prinzipien und Werte, entlang derer Governance-Aktivitäten auf der zweiten sowie ersten Ebene letztlich ausgerichtet und bewertbar gemacht werden.

Im weitesten Sinne ist Meta-Governance bei Kooiman der „process in which the discussion, formulation and application of values, norms and principles for governance takes place” [10, p. 1761]. Die Ebene der Meta-Governance umfasst in der Governance-Praxis also Prinzipien und Werte, die die Grundlage für spezifische (und nicht andere) Governance-Konstellationen bilden oder eine Neuausrichtung entlang dieser Werte erlauben. Diese können explizit oder implizit vorliegen. Die Ebene der Meta-Governance ist bei Kooiman nicht eindeutig definitorisch abgesteckt. Studien im Feld der Governance-Forschung verwenden die Ebene vorwiegend im Sinne „government plus governance“ [10, p. 1774]. D.h., es wird tendenziell eine Rolle der „meta-governors“ impliziert, die durch staatliche Stellen verkörpert werden. Das Verständnis von Meta-Governance in diesem Aufsatz orientiert sich an diesem Verständnis, ist aber enger angelegt und soll als (explizit oder implizit vorliegende) Werte und Ziele verstanden werden, die Institutionalisierungen auf der zweiten bzw. Handlungen auf der ersten Governance-Ebene anleiten oder (un)möglich machen. Dies liegt näher an einer Verwendung des Konzeptes in der Planungsliteratur, wonach Meta-Governance durch „Leitbilder“ verkörpert wird [9].

B. Techniksoziologie & Science and Technology Studies

Ergänzend nimmt unser Theorieframework Bezug auf Ansätze der Techniksoziologie, welche seit den späten 1980er Jahren zunehmend den prozessualen Charakter von Technik in den Blick nehmen. Dies kann nachvollziehbar machen, warum Digitalisierungsprozesse in der lokalen Ausgestaltung Veränderungen durchlaufen und z.T. starke Unterschiede aufweisen. Der deutsche Soziologe Werner Rammert versteht Technik beispielsweise als einen „Prozess der Technisierung“ [11], [12, p. 129]. Diese Definition verweist auf das in techniksoziologischen Ansätzen stets betonte enge Wechselverhältnis zwischen Technik und dem sozialen, kulturellen Kontext, innerhalb dessen sich diese entwickelt, durchsetzt (oder auch nicht) und Anwendung findet. Trotz der

Heterogenität des Feldes, destabilisieren techniksoziologische Ansätze tendenziell technodeterministische Annahmen, nach welchen menschliche Entwicklung mit technologischen Entwicklungen gleichgesetzt werden könne und einem linearen Entwicklungspfad folge. In der heutigen Techniksoziologie wird die Trennung selbst zwischen Technik und Sozialem zunehmend in Frage gestellt, sodass man beispielsweise von soziotechnischen Konstellationen [11] oder soziotechnischen Systemen [13, p. 574] spricht, in denen sich Handlungsträgerschaft auf Mensch und Technik verteilt. Damit kritisierte man technikessentialistische Lesarten technischer Objekte als dem Sozialen enthobene Entitäten und stellte analytische Instrumente zur Verfügung, die das Wechselverhältnis integriert bearbeitbar machen sollten.

Digitalisierung funktioniert nicht ohne Technik, beschreibt aber weitaus mehr als nur ihre technische Grundlage. Digitale Technologien, ihre Infrastrukturen und die Möglichkeiten, die sie anbieten, sind entsprechend keine fixen Entitäten, die als passives Objekt von Governance-Praktiken zu verstehen sind. Ihre Entwicklung, Gestalt und ihre ‚angemessene' Verwendung unterliegen einem fortlaufenden Wandel, der nicht linear verläuft, sondern durch Brüche, Aneignungen, Stabilisierungen oder Pfadabhängigkeiten charakterisiert ist sowie diskursive Zukunftsbilder mitgestaltet und von diesen geprägt ist.

Entlehnt aus Ansätzen der Techniksoziologie und Science and Technology Studies, soll Digitalisierung in diesem Aufsatz entsprechend nicht nur als technisches, sondern auch (!) als ein sozial konstruiertes Phänomen verstanden werden [14]. Eines, das nicht einfacherweise de novo geplant werden kann, sondern auf eine „installierte Basis", d.h. bereits vorhandene organisationale, technische und institutionelle Anordnungen trifft [15, p. 113]. Die konkrete Ausgestaltung, sein Lösungshorizont und die in der Folge als angemessen empfundene Umsetzung eines digitalen Wandels und dafür eingesetzte Technologien sind entsprechend durch involvierte Akteure (1) sowie einen institutionellen Kontext (2) geprägt [16]. Den Ausgangspunkt für diese eher konstruktivistisch angelegte Technikforschung bilden „relevant social groups" [16, p. 26]. Technik, ihre Entwicklung und Implementierung haben unterschiedliche Bedeutungen für soziale Gruppen. Dabei ist auch von Interesse, welche ExpertInnen bei Konsultation und Bewertung technologischer Implementierungen herangezogen werden. Ob Digitalisierung von Beteiligten also als ein vornehmlich technisches, ökonomisches, organisatorisches oder politisches Problem artikuliert und behandelt wird, wird auch im Kontext unterschiedlicher Akteurskonstellationen verhandelt [17].

Die den Governance-Aktivitäten zugrundeliegende Technik (als Objekt der Governance) ist jedoch nicht beliebig und ‚nur' durch soziale Interessen gestaltet [18]. Freiheitsgrade bei der technologischen Implementierung werden auch durch (digitale) Technologien, Infrastrukturen und ihre spezifischen Funktionsweisen geprägt, beispielsweise dann, wenn bestimmte technische Schnittstellen, intentional oder nicht, Kontrolle über Ressourcen wie Marktzugang ausüben und kommunale Akteure in der Folge in ihren Entscheidungen (auf andere Systeme umzusteigen) eingeschränkt sind [19, p. 4], [20]. Oder dann, wenn plattformbasierte Technologien und ihre Affordanzen (d.h. Handlungsangebote) andere Formen der organisatorischen Zusammenarbeit nahelegen und routinierte Abläufe in Frage stellen.

C. *Forschungskonzept und empirische Analysen*

Grundlage dieses Aufsatzes sind die im September/Oktober 2021 und März 2022 durchgeführten Interviews mit Mitgliedern aus dem Gemeinderat sowie Fachbereichs- und Referatsleitungen (n=17). Zur Auswertung genutzt werden ein ground theory inspirierter Ansatz der Kategorienbildung [21] und sozialwissenschaftliche Hermeneutik [22]. Punktuell werden außerdem Erkenntnisse aus Gesprächen mit den Mitarbeitenden des Bürgerbüro Bauens und Projektbeteiligten des Digitalen Bauamtes hinzugezogen, jedoch nur soweit sie das Thema Governance berühren. Darüber hinaus finden Desk-Recherchen zum politischen Rahmen kommunaler Digitalisierung und eine Sichtung der Forschungsliteratur zum Thema E-Government, Smart Cities und (digitaler) Infrastruktur in diesem Aufsatz Beachtung.

Die folgende ABBILDUNG 1 visualisiert das Forschungskonzept des gesamten Projekts.

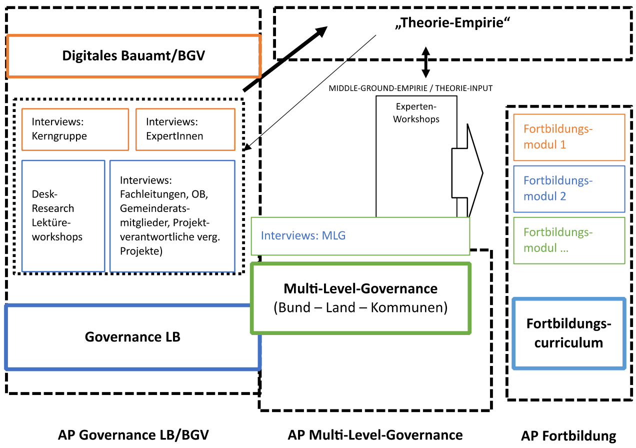


ABBILDUNG 1: DAS FORSCHUNGSKONZEPT DES PROJEKTS.

III. DER ANFORDERUNGSKONTEXT: DAS OZG

Deutschland rangiert beim Thema Digitale Verwaltung in einschlägigen Rankings in der Regel auf den hinteren Plätzen [23, pp. 30-31]. Auch das 2013 in Kraft getretene E-Government-Gesetz und eine darauffolgende Evaluation aus dem Jahre 2018 offenbarte die Schwierigkeiten, eine föderal fragmentierte Verwaltungslandschaft ineinander zu integrieren (BT-Drucksache 19/10310). Projekte, wie die elektronische Gesundheitskarte, der elektronische Personalausweis oder rechtssichere Übertragungssysteme (De-Mail), gelten weitgehend als nicht erfolgreich, sodass Stimmen aus den Verwaltungswissenschaften eine „Geschichte des Scheiterns" konstatieren [24, p. 415].

Das „Gesetz zur Verbesserung des Onlinezugangs zu Verwaltungsleistungen" ist der jüngste Versuch des Gesetzgebers, die digitale Verwaltung voranzutreiben. Es verpflichtet den Bund, die Länder und die Kommunen bis zum Ende des Jahres 2022 dazu, ihre Verwaltungsleistungen elektronisch anzubieten, eingebettet in eine entsprechende IT-Infrastruktur, die Nutzern einen einfachen Zugriff darauf ermöglicht. Kommunen sind als Vollzugseinheit der meisten Verwaltungsleistungen besonders stark vom OZG betroffen, s. ABBILDUNG 2.

ABBILDUNG 2: ÜBERSICHT DER ZUSTÄNDIGKEITEN VON VERWALTUNGSLEITUNGSLEISTUNGEN BEI BUND, LÄNDERN UND KOMMUNEN. QUELLE: BMI.

Als Maßstab zur Erfüllung gilt ein Reifegradmodell mit vier bzw. fünf unterschiedlichen Stufen, s. ABBILDUNG 3.

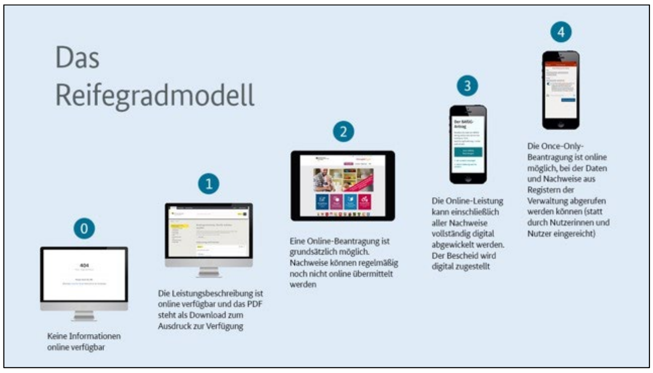


ABBILDUNG 3: DAS REIFEGRADMODELL DES BMI

Das Gesetz selbst legt nicht eindeutig fest, ab wann Verwaltungsleistungen „elektronisch“ vorliegen. Ein Beschluss des IT-Planungsrates legt nahe, dass für eine OZG-konforme Umsetzung zum Ende der Frist mindestens die Stufe 3 des Reifegradmodells erforderlich ist [25, 26]. Im Reifegradmodell bedeutet dies, dass die Leistung „einschließlich aller Nachweise vollständig digital abgewickelt werden kann“ und Bescheide ebenso digital zugestellt werden (Online unter: https://www.onlinezugangsgesetz.de/Webs/OZG/DE/grundlagen/info-ozg/info-reifegradmodell/info-reifegradmodell-node.html (zuletzt abgerufen am 01.07.2022)). Das OZG orientiert sich hierbei an der Perspektive der Antragsstellenden. Für Verwaltungen bedeutet dies also a) die Annahme digitaler Dokumente zu ermöglichen und b) den digitalen Versand eines Bescheides rechtssicher gestalten zu können. Alles, was dazwischen passiert, ist im OZG nicht näher geregelt.

Grundlage für das OZG bildet der OZG-Umsetzungskatalog, welcher die über 7.000 Verwaltungsleistungen des Leistungskataloges der öffentlichen Verwaltung (LeiKa) zu 575 OZG-Leistungsbündeln zusammenfasst. Der aktuelle Umsetzungskatalog ist auf der Informationsplattform der FITKO bzw. des BMI zu finden. Der Bereich ist nur nach Anmeldung zugänglich: https://informationsplattform.ozg-umsetzung.de (zuletzt abgerufen am 01.07.2022). Die OZG-Bündel sind in 14 Themenfelder gegliedert und letztere wiederum in einzelne Lebenslagen unterteilt (Online unter: https://www.onlinezugangsgesetz.de/Webs/OZG/DE/grundlagen/info-ozg/info-leistungen/info-leistungen-node.html (zuletzt abgerufen am 01.07.2022)).

Das OZG behandelt Verwaltungsdigitalisierung relativ eng unter zwei Aspekten: BürgerInnen sind vor allem Nutzende von Verwaltungsleistungen. Entsprechend bedeutet der Fokus auf BürgerInnen in diesem Kontext die Nutzungsfreundlichkeit von Antragsstellungen (oder seltener, die automatisierte Zustellung von Verwaltungsleistungen). Die Rolle der Verwaltungen wiederum wird tendenziell auf die Bereitstellung von Verwaltungsleistungen reduziert.

IV. DAS FALLBEISPIEL: LUDWIGSBURG UND DAS DIGITALE BAUAMT

A. *Ludwigsburg*

Das Bauamt der Stadt Ludwigsburg ist Konsortialpartner des Projekts. Die Stadt wurde als Case Study ausgewählt, weil sie hinsichtlich der Umsetzung des Reifegradmodells des OZG im digitalen Bauantragsverfahren / digitalen Bauamt ambitioniert ist und potentiell das gesamte Spektrum des eingangs skizzierten weiten Digitalisierungsverständnisses abbildet.

Ludwigsburg ist eine mittelgroße Stadt in Baden-Württemberg in der Metropolregion Stuttgart. Sie ist die Kreisstadt des Landkreises Ludwigsburg und mit knapp 94.000 Einwohnern die größte Mittelstadt (20.000 – 99.999 EW) und insgesamt zehntgrößte Stadt in Baden-Württemberg.

B. *Der digitale Bauantrag & das digitale Bauamt*

Das Projekt des digitalen Bauamtes ging auf unterschiedliche Rahmenbedingungen zurück. Zum einen kam es 2019 zu einer Novelle der Landesbauordnung in Baden-Württemberg. Diese legte einen gesetzlichen Anspruch für die Einreichung digitaler Antragsdokumente fest, sodass ab Januar 2022 Anträge nicht mehr in analoger Form eingefordert werden können (IV22:82). Hinzu kam die Pandemie, welche das Arbeiten von zu Hause notwendig machte. Auf der anderen Seite gab es nach wie vor das OZG. Im Bürgerbüro Bauen entschied man sich entsprechend, diesen Rahmen als „Chance“, „proaktiv“ zu nutzen (IV19:4), die Digitalisierung der Baugenehmigung „größer [zu] denken“ (IV23:20) und sich nicht auf den gesetzlichen Mindestanspruch zu beschränken (ebd.:18). Aus dem Bürgerbüro Bauen heraus entstand so die Idee eines Projektes des Digitalen Bauamtes. Dieses umfasst verschiedene Teilprojekte, wovon die Digitalisierung des Bauantragsverfahrens aktuell (Stand Juni 2022) den größten Raum einnimmt.

Das Projekt des digitalen Bauamtes wird, vor allem in Form des OZG-Koordinators, von Seiten der Organisationsentwicklung (Fachbereich Organisation und Personal) begleitet. Dieser begleitet den Prozess, neben 141 anderen in Ludwigsburg zu digitalisierenden Verwaltungsleistungen, unter Aspekten der Prozessentwicklung (IV19:8). Als Projektmanager koordiniert er zwischen seinem Fachbereich (Organisation & Personal), einer stellvertretenden Person aus dem Fachbereich Digitalisierung & IT, sowie dem „Kernteam“ aus dem Bürgerbüro Bauen, welches aus Stellvertretenden aller am Baugenehmigungsprozess beteiligten Berufsgruppen besteht (Baurecht, Bauverständige, Assistenz). Das Projekt nimmt an dieser Stelle die bereits im Bauamt etablierte interdisziplinär organisierte Bearbeitungsform auf, mit welcher in Ortsgruppen Bauanträge bearbeitet werden. Eine Projektlenkungsgruppe besteht ferner aus einem Stellvertreter des Stadtplanungsamtes, der Leitung des für das Bürgerbüro Bauen verantwortlichen Dezernats (IV) sowie der Leitung des Bauamtes.

V. Erste empirische Ergebnisse

Der folgenden Analyse liegen 17 leitfadengestützte Interviews zugrunde (vgl. Abb. Forschungskonzept), die inhaltlich codiert und hermeneutisch analysiert wurden [21], [22]. Die so gewonnenen Aussagen wurden in den Kontext des theoretischen Rahmens – Governance, Techniksoziologie, Science & Technology Studies – gestellt. Ziel war es, hierdurch – sowie angereichert um die Ergebnisse des Desk Research – die erkenntnistheoretischen Grenzen einer Case Study zu überwinden und zu generalisierten Aussagen zu kommen.

Im Folgenden verzichten wir auf die Mikroanalyse und präsentieren maßgeblich die generalisierten Aussagen zu den zwei Erkenntnisinteressen dieses Papiers: Erstens die zentralen Spannungsfelder, die die Digitalisierung der kommunalen Verwaltung bzw. die kommunalen Digitalisierungsprozesse bestimmen (A). Zweitens identifizieren wir – noch tentativ – Erfolgsfaktoren kommunaler (Verwaltungs-)Digitalisierung (B).

A. Spannungsfelder

Im Folgenden sollen einige generalisierte Spannungsfelder skizziert werden, die bei der Gestaltung kommunaler Digitalisierungsprozesse relevant werden können. Zum einen können sie Tendenzen darstellen, entlang derer Digitalisierungsprojekte verortet oder primär bearbeitet werden können. Zum anderen ließe sich hypothetisch formulieren, dass die Wirksamkeit von Governance-Konstellationen dadurch mitgestaltet wird, wie gut sie mit den Spannungsfeldern umgehen und diese bearbeitbar halten kann.

1) Querschnittsaufgaben vs. Ressortaufgaben

Digitalisierungsprojekte in Kommunen und ihren Verwaltungen lassen sich grob entlang eher gesamtstädtisch/querschnittsorientierter und eher fachbehördlich orientierter Bezugsrahmen einteilen. Da Verwaltungen eine historisch gewachsene Ressortstruktur aufweisen, lässt sich eine Tendenz in Verwaltungen beobachten, Digitalisierungsprojekte in ähnlicher Weise zu ordnen. Das Verkehrsamt plant digitale Mobilität, das Bauamt digitale Bauanträge, die Geschäftsstelle verteilt digitale Geräte an ihre Verwaltungsmitarbeitenden und Gemeinderatsmitglieder. All diese Projekte können unabhängig voneinander ‚Erfolg' haben. Es kommt aber vor, dass A) entweder punktuelle Berührungspunkte zwischen den Projekten entstehen müssen (z.B. wenn die Bearbeitung einer digitalen Baugenehmigung auch die Mitarbeit einer daran beteiligten Behörde erfordert) oder B) Gesamtstrategien existieren, die Anforderungen an die Einzelprojekte stellen. Diese können innerhalb der Verwaltung vorliegen, aber ebenso durch gesetzliche Anforderungen von Bund und Land verkörpert werden. Das Spektrum von Digitalisierungsprojekten oder -visionen muss also eine Ordnung, eine Hierarchie erhalten. Gesamtstädtisch entwickelte Strategien können von Fachbehörden nicht umgangen werden. Als Schnittstelle könnten Querschnittseinheiten (Digitalisierungsbeauftragte / IT / CDO /CIO; Beiräte; Referate; Ausschüsse etc.) agieren. Diese übersetzen bestenfalls zwischen Ideen der Einzelprojekte und einer Integration in gesamtstädtische Systeme.

2) Zentrale Planung/Steuerung vs. dezentrale Planung/Steuerung

Dem oben eher territorial angelegten Bezugsrahmen ließen sich außerdem weitere Spannungsfelder zuordnen: so das zwischen zentraler Planung und Steuerung auf gesamtstädtischer Ebene versus dezentraler Planung und Steuerung auf fachlicher Ebene. Vor allem top-down organisierte Integrationsmaßnahmen stehen vor der Herausforderung, das Beharren von unten auf fragmentierte, spezialisierte (und dadurch bestenfalls wirksame) Systeme und das Streben von oben nach Vereinheitlichung von Systemen (mit der Gefahr, lokale Wirksamkeit zu beeinträchtigen) miteinander zu verhandeln. Das Streben nach Vereinheitlichung technischer Systeme kann ebenso als Zuständigkeitskonkurrenz und Abgabe von Kompetenzen, Autonomie oder Kontrolle über Ressourcen erfahren werden, beispielsweise dann, wenn die für die lokale Bearbeitung eines Prozesses (Baugenehmigung) notwendige Fachkompetenz einem IT-strategischen Imperativ der Gesamtstadt untergeordnet wird.

Es gilt zu bestimmen, welche Aspekte von Digitalisierung zentral und welche dezentral gesteuert werden müssen. Sofern dies nicht von Beginn an geplant werden kann, kann sich diese Verteilung im Laufe einzelner Projekte verschieben und erfordert mitunter spezifische Anpassungen.

Dies kann ein Dilemma sein. Denn zum einen sind klare Zuständigkeiten wichtig, zum anderen ist nicht auszuschließen, dass fallspezifische Anpassungen Abweichungen von diesen Zuständigkeiten erfordern. Auf einer abstrakteren Ebene ließe sich dieses Zusammenspiel als eine Mikro-Variante des Collingridge-Dilemmas verstehen [17, p. 127]. An anderer Stelle wurde es auch das Problem der „blind giants" genannt [26, p. 154]. Es bezeichnet vornehmlich ein Steuerungsdilemma zur Regulierung von Technologien auf Makro-Ebene: zu dem Zeitpunkt, zu dem technologische Entwicklungen noch gut gesteuert und reguliert werden können, fehlt tendenziell das Wissen über schlussendliche Risiken und Nutzen der Technologien. Sind Probleme und Risiken bekannt, ist die Entwicklung von Technologien meist bereits fortgeschritten, so dass Kursänderungen und Steuerung sowie Anpassungen von Entwicklungen nur noch schwierig vorgenommen werden können. Die Parallele zu Kommunen kann sein, dass (zentrale wie dezentrale) Zuständigkeiten zu einem Zeitpunkt etabliert werden, wenn Wissen über Anforderungen, Probleme und Risiken noch nicht gänzlich vorhanden ist.

3) Stabilität vs. Flexibilität

Dies ist ein Spannungsfeld, welches vor allem digitale Infrastrukturen auszeichnet und mit dem Spektrum Gesamtstadt-Fachbehörde korrespondiert [26] [28]. Digitale Infrastrukturen (und entwickelte Visionen diesbezüglich) müssen hinreichend konkret sein, um Interoperabilität sowie gemeinsame Ziele gewährleisten zu können. Sie müssen aber ebenso ausreichend Flexibilität ermöglichen, falls inkrementell weitere Komponenten oder Ideen entwickelt oder ausgetauscht werden sollen, oder gesetzliche Anforderungen weitere Entwicklungen notwendig machen (siehe z.B. Registermodernisierung).

Die Zeitlichkeit digitaler Infrastrukturen spielt hierbei eine nicht unerhebliche Rolle. In Anlehnung an Jay Lemkes Verwendung des aus der Evolutionsbiologie stammenden Begriffes der „Heterochronie", betonen [29, pp. 107-108] die Relevanz sich überlagernder zeitlicher Skalen und Verläufe bei digitalen Infrastrukturen, welche deren Entwicklung verkompliziert. Allgemein bezeichnet Heterochronie Variationen in den Parametern zeitlicher Veränderung verschiedener Teile eines Systems. Übertragen meint dies: Komponenten von technologischen Systemen sind mitunter veraltet, während sich dieses noch im Aufbau befindet; soziale Gruppen haben unterschiedliche (Lern-)Zyklen, sich Programme anzueignen; oder Interesse an der Nutzung von Anwendungen tritt auf, während Entwickler nur noch geringes Interesse und in der Folge weniger Kapazität für Instandhaltung und Aktualisierungen haben.

4) Digitalisierung vs. Digitalität

Im Englischen wird zwischen „digitization" und „digitalization" unterschieden. Ersteres meint den technischen Prozess von analoger in digitale Information, letzteres die Restrukturierung des ‚Sozialen' entlang (Möglichkeiten) digitaler Technologien [30]. Im Deutschen sind derartige Unterscheidungen zumindest im alltäglichen Sprachgebrauch weniger verbreitet. Gleichwohl gibt es Versuche, Digitalisierung als (nicht nur, aber eher technischen) Prozess von (einer Kultur der) Digitalität zu unterscheiden, welche nach Stalder eintritt, sobald Bedingungen, innerhalb derer Menschen handeln (und sich erfahren), maßgeblich durch digitale Medien und ihre Funktionsweisen konstituiert werden [31]. Digitalität wäre also das, was durch Prozesse der Digitalisierung ermöglicht werden kann. In den Politikwissenschaften wurde diesbezüglich eine Unterscheidung zwischen enger und weiter Digitalisierung vorgeschlagen [32].

Anwendungsbezogen gedacht, ließe sich auch der technische Prozess von Digitalisierung entlang eher enger oder weiter Digitalisierung aufmachen, wobei enge Digitalisierung die Überführung von Informationen in digitale Medien wäre, ohne zugrundeliegende Informationen grundsätzlich anders anzuordnen, während weitergehende Digitalisierung Informationen digital abbildet, aber durch die Logik der zugrundeliegenden Infrastrukturen neu ordnet (z.B. Plattformisierung). Ein schlechter (oder auch: ein guter) analoger Prozess wird nicht automatisch besser, wenn er digital nachmodelliert wird. Mit anderen Worten: eine Elektrifizierung analoger Prozesse führt nicht notwendigerweise zu erhofften Produktivitätssteigerungen, solange nicht die spezifische Wirkungsweise digitaler Infrastrukturen mitgedacht wird und Prozesse durch die Linse neuer Technologien mit angepasst werden. Dies wird auch als „productivity paradox" bezeichnet [33, p. 233]. Das klassische Argument ist hier vom Ökonom Paul David: elektrische Dynamos waren schlechte Dampfgeneratoren und der Computer war eine schlechte Schreibmaschine, sodass es nach ihrer Einführung zunächst zu Produktivitätsrückgängen kam, bis neue Arten des Denkens *durch* die neuen Technologien entstanden und Ausdruck in Infrastrukturen fanden, die die neuen technologischen Möglichkeiten aufnehmen konnten.

Auf der anderen Seite kann sich aus einer zu engen Fokussierung auf die Wirkungsweisen computerisierter Steuerung auch eine Tendenz der Disziplinierung einstellen, sobald der soziale Kontext von Digitalisierung ignoriert, andere nicht-maschinelle kognitive Modi untergeordnet werden oder eine Neuausrichtung von Prozessen zugunsten digitaler Technologien Menschen dazu anhält, wie ein Computer zu arbeiten [34] [35].

5) ‚Smart City' vs. ‚E-Government'

Dies ist eher als konzeptuelles Spannungsfeld zu verstehen. In der Stadtforschung erhält das Thema städtischer Digitalisierung vor allem durch das Konzept der Smart City oder Digitalen Stadt Aufmerksamkeit. Verwaltungs- und politikwissenschaftliche Ansätze haben entsprechend ihres Forschungsobjektes tendenziell Konzepte wie E-Government, E-Governance oder E-Democracy im Blick. Welche räumlichen und materiellen Auswirkungen beispielsweise digitale Plattformen auf städtisches Leben und Arbeiten haben [36] [37] oder wie digitale Konzepte der Stadt vor allem durch Unternehmen öffentlichkeitswirksam gemacht werden, um neue Märkte zu erschließen [38], sind eher Themen, die Stadtforschung beschäftigt.

Im Bereich des E-Government hingegen geht es u.a. um Regierungs- und Verwaltungspraktiken, -strukturen sowie ihre Rolle in Regierungssystemen. Hier steht der räumliche oder spezifisch urbane bzw. städtische Aspekt, den v.a. stadtgeographische Arbeiten bemühen, weniger im Blick. Städtische Digitalisierung oszilliert also zwischen multiplen Begriffsverständnissen. Mal meint Stadt die administrative Einheit, mal ist ‚nur' die Kommunalpolitik gemeint, mal ist die Erfahrung von Stadtnutzenden gemeint (sowohl mit Blick auf Verwaltungsleistungen, als auch mit Blick auf das Erfahren von Stadt als gebaute Umwelt). Integrierte Stadtentwicklungskonzepte bearbeiten Digitalisierung tendenziell unter anderen Aspekten als es die E-Government-Strategie des Bundes beispielsweise tut. Das hat Konsequenzen für die Organisation von Digitalisierung und daraus folgende Zuständigkeiten.

6) Politik (Legislative) vs. Verwaltung (Exekutive)

Eine verbreitete Perspektive auf Politikgestaltung ist die der Gewaltenteilung zwischen Legislative und Exekutive. Verwaltung kommt tendenziell letztere Rolle zu. Im Feld der Digitalisierung ist aber nicht ausreichend klar, welche Aspekte einer technischen Lesart von Digitalisierung u.U. politische Legitimationen erfordern und nicht einfach ‚ausgeführt' werden können. Wenn Verwaltungen die Grundlage für lokale Regierbarkeit politischer Sachverhalte bilden, beispielsweise durch die Erhebung von Daten, Planungsmodelle, Statistiken, dann können veränderte Umstände dieser Herstellung von Planbarkeit durch neue Technologien (wie digitale Medien), ggfs. politisch legitimierte Entscheidungen erfordern.

7) Organisation von Digitalisierung vs. Organisation durch Digitalisierung

Analytisch lassen sich Digitalisierungsbestrebungen in ihre Etablierung und ihre Effekte unterteilen. Im Feld der Digitalisierung kann das Thema der BürgerInnenbeteiligung mit Blick auf digitale Beteiligungsmethoden beleuchtet werden. Ebenso kann BürgerInnenbeteiligung in diesem Feld aber auch bedeuten, über eine Digitale Agenda abzustimmen. Ersteres meint Digitalisierung als *Mittel zur Rekonfiguration einer Praxis*, letzteres meint Digitalisierung als *Objekt der Praxis*. In konkreten Projekten lassen sich diese Dimensionen nicht immer einfach trennen. Wer eine Verwaltungsleistung digitalisieren möchte, muss antizipieren, welche Momente im Prozess durch digitale Mittel verändert werden und dadurch u.U. andere Anforderungen an den Herstellungsprozess von Digitalisierung als Objekt (von Governance, Organisation, Projektmanagement etc.) stellen.

8) Betroffenheit: Externalisierte Perspektive vs. Internalisierte Perspektive

Gemeint ist die Betroffenheit des Themas der Digitalisierung von außen und von innen. D.h., ein Bürgerkonto mobilisiert BürgerInnen als Adressaten und Nutzende der Digitalisierung. Intelligente Verkehrssteuerung mobilisiert Verkehrsnutzende als Betroffene. Die Elektronische Akte wiederum mobilisiert tendenziell Verwaltungsmitarbeitende und Organisationsprozesse innerhalb der Verwaltung, während BürgerInnen nur indirekt betroffen wären (z.B. da künftig u.U. elektronische Interaktionsformen mit der Verwaltung möglich werden). Es kann hierbei ebenso zu Spannungen zwischen den Betroffenheiten kommen, beispielsweise zwischen effizienzorientiertem Verwaltungshandeln und Bürgerfreundlichkeit.

9) Technisches Wissen vs. praktisches Wissen

Das Verhältnis zwischen formalen und informalen Wissensbeständen ist gerade im Feld der Digitalisierung ein wirksames. Dort, wo Arbeitsroutinen in der Verwaltung explizit vorliegen und Handeln anleiten (wie z.B. in Formularen), sind Übersetzungen in digitale Technologien u.U. weniger problematisch als dort, wo technisches mit praktischem Wissen konkurriert. ExpertInnen der Bearbeitung von Bauanträgen wissen, dass bestimmte Momente in Baugenehmigungsprozessen politischer Intervention unterliegen, ein gewisses Maß an Auslegung (von Baurecht) ermöglichen oder bestimmte Funktionen notwendig sind, um im Fachbereich vorhandene Arbeitsweisen aufzufangen, die vom Protokoll abweichen.

Ein IT-Beauftragter mag eine funktional effektive Datenmanagement-Lösung vorschlagen, um eine integrierte IKT-Infrastruktur aufzubauen. Diese Lösung wiederum kann aus fachlicher Hinsicht von Abteilungen abgelehnt werden, sofern sie nicht in der Lage ist, die für die Bearbeitung von Baugenehmigungen notwendigen praktischen Anforderungen angemessen abzubilden. Dies kann sich auf die Unvereinbarkeit mit anderen formalen Wissensbeständen beziehen (beispielsweise Baurecht und dessen Auslegung), sowie auf die lokal vorliegenden Arbeitsweisen. Die Aussage eines von uns befragten Gemeinderatsmitgliedes, das auch als ArchitektIn tätig ist, illustriert in leicht abgewandelter Form, wie dieses Spannungsfeld erfahrbar werden kann:

„Das ist wie bei mir im Beruf, wenn ich ein CAD-Programm oder ein Ausschreibungsprogramm habe. Man merkt einfach, der Programmierer ist nicht der Praktiker. Da gibt es manchmal beim CAD irgendwas, wünscht man sich einfacher oder eine Funktion, einen Text, ich schicke den rüber. Aber ich muss vorher fünf Sachen anklicken, bis ich den Text verschieben kann so irgendwas. Kann aber dafür ein vierfach gekrümmtes Tonnendach konstruieren, was ich sowieso nie brauche.“ (IV11:52)

Das Spannungsfeld ließe sich unterschiedlich konzeptualisieren und weiter abstrahieren. In der Literatur finden sich unterschiedliche Begriffspaare, die sich im Detail unterscheiden, aber eine ähnliche Spannung problematisieren. Der Politikwissenschaftler und Anthropologe James C. Scott beispielsweise kontrastiert das aus staatlicher Regierungsperspektive notwendige ‚techne‘ zur Herstellung von Regierbarkeit mit lokalen Wissensbeständen der ‚metis‘, zu welchen erstere in Konkurrenz stehen können [39]. In Anlehnung an Michael Polanyi's „tacit knowledge“ [40], d.h. implizitem Wissen, das unausgesprochen vorliegt und nicht einfach explizierbar ist, unterscheidet der Soziologe Harry Collins zwischen explizitem und implizitem Wissen [35].

Der Unterschied zwischen explizitem und implizitem Wissen verweist auch darauf, dass die Spannung zwischen technischem und praktischem Wissen nicht notwendigerweise von der Nähe zum Arbeitsgegenstand abhängt, wie es die o.g. Beispiele nahelegen könnten. Vielmehr finden wir im Material auch Hinweise darauf, dass es beispielsweise bei der Bearbeitung von Bauanträgen Routinen gab, deren Relevanz erst auffiel, als man begann digitale Anträge zu bearbeiten.

10) Funktionalität vs. Normativität

Was aus Perspektive der Softwareentwicklung funktionieren mag, kann sich in der Praxis als wenig handhabbar (1) oder politisch unerwünscht herausstellen (2). Technologien können funktionieren, aber als wenig sinnvoll erachtet werden. Umgekehrt können für sinnvoll erachtete Technologien wenig funktional (oder schlecht skalierbar) sein.

11) De facto Standards vs. de jure Standards

Vor allem digitale Infrastrukturen sind im Vergleich zu analogen Bearbeitungsstrukturen weitaus stärker auf bestimmte Standards angewiesen, die Interoperabilität ermöglichen. Während ein Blatt Papier in allen Verwaltungsabteilungen, unabhängig dessen, was auf ihm steht, ein Blatt Papier bleibt, sind digitale Sprachen zwischen IT-Systemen vielfältiger und erfordern Vereinheitlichungen der Sprachen oder Übersetzungen zwischen diesen Sprachen. Insofern kommt dem Feld der Standardisierung eine wichtige Rolle bei der Implementierung digitaler Systeme und Kommunikationsinfrastrukturen zu. Der Bund gibt bereits an vielen Stellen Standards zur Kommunikation vor, ein Beispiel ist das XOEV-Rahmenwerk, welches Datenstandards setzt. Die top-down-Gestaltung solcher Standards ist aber eingeschränkt durch die historisch unterschiedlich gewachsenen Infrastrukturen in deutschen Verwaltungen und deren Verortung in öffentlicher und privater Hand. D.h., de jure-Standards treffen auf de facto-Standards. Erstere sind gesetzlich vorgegeben, letztere (v.a.) durch Marktmechanismen herausgebildet. Google ist ein de facto Standard im Bereich Suchmaschinen, Microsoft Office-Programme sind in bestimmten Anwendungsbereichen de facto-Standard bei Büroprogrammen. Diesen Programmen zugrundliegende (technische und häufig proprietäre) Standards sind nicht formal festgelegt. Es gibt keine vertraglichen Bindungen, diese nutzen zu müssen. Vielmehr gestalten Netzwerkeffekte mit, dass sich bestimmte Programme durch Marktmacht etablieren konnten, *als ob* sie einen Standard darstellen würden. Erfolgreiche Folgetechnologien werden auch daran gemessen, inwiefern sie Schnittstellen zu diesen de facto Standards herstellen können. Im Bereich der Verwaltungsdigitalisierung kann sich dieses Spannungsfeld im Feld der Fachanwendungen ausdrücken, sobald die Wahl spezifischer Programme durch die Anschlussmöglichkeiten an alte Fachanwendungen limitiert werden. Dies geht in zwei Richtungen. Zum einen gibt es Hürden bei der Herstellung von Schnittstellen aus neu angeschafften Anwendungen in die bisherige Fachanwendung, zum anderen ist die Herstellung von Schnittstellen zu de facto Standards (wie Email/Outlook, Word, PDFs) aus den bisherigen oder geplanten Anwendungen heraus eine Herausforderung.

B. Erfolgsbedingungen

Da sich Ludwigsburg inmitten eines Umstrukturierungsprozess befindet und auch Teilprojekte wie das Digitale Bauamt nicht abgeschlossen sind, ist eine eindeutige Identifizierung von Erfolgsfaktoren noch nicht möglich, zumal spezifiziert werden müsste, *wessen* Erfolg gemeint ist. Es lassen sich aus dem Material aber ein paar, zunächst unsortierte, Bedingungen aus dem Scheitern vergangener Digitalisierungsprojekte in Ludwigsburg ableiten. Diese sind zunächst vor dem Hintergrund des Materials aus Ludwigsburg zu verstehen. Inwiefern sind die folgenden Generalisierungen noch tentativer Art.

1) Schnittstellen zwischen Kommunalpolitik und Verwaltungsabteilungen

Digitalisierung erfordert eine integrierte Bearbeitung, da sie ressortübergreifende Betroffenheiten erzeugt. In der Vergangenheit wurde Digitalisierung in Ludwigsburg primär ohne die Einbindung des Gemeinderates und der Fachbehördenleitungen vorangetrieben. Ein organisatorischer Unterbau innerhalb der Verwaltung ist aber Voraussetzung, dass Digitalisierungsambitionen auch tatsächlich umgesetzt werden können. Der Gemeinderat als politisches Gremium wurde außerdem über Entscheidungen nur informiert. Dadurch konnte dieser zunächst keine Voraussetzungen schaffen, die es Fachbehörden ermöglicht hätten, Digitalisierung gemeinsam umzusetzen. Kooperationen mit verwaltungsexternen Akteuren müssen in interne Verwaltungsstrukturen integriert werden. Dies gilt auch für wissenschaftliche oder wirtschaftliche PartnerInnen, deren Arbeit von verwaltungsinternen Bewertungsmechanismen gerahmt sein muss. Soll eine Digitalisierungsstrategie oder Agenda diesen Rahmen bilden, können Defizite bei der Umsetzung entstehen, sobald die Entstehung vor allem externalisiert wird. Dies gilt auch für die Einbindung zivilgesellschaftlicher Expertise und bürgerschaftlicher Bedarfe, die auf dem Weg dorthin gesammelt werden. In Ludwigsburg führte man ambitionierte Zukunftskonferenzen durch, deren Ergebnisse fanden jedoch keinen Eingang in die schlussendlich verabschiedete Digitale Agenda und erhielten aufgrund mangelnder Schnittstellen zu Digitalisierungsprojekten keine angemessene Berücksichtigung.

2) Unterstützung durch den Oberbürgermeister

Eine Bedingung für eine erfolgreiche, vor allem weitergehende Auseinandersetzung mit kommunaler Digitalisierung ist die Unterstützung durch die politische Leitung. Ohne eine solche Unterstützung kann es sich als schwierig erweisen, Steuerungseinheiten in der Verwaltung zu etablieren und Budgets freizustellen. Das Material legt aber nahe, dass sie kein Garant für erfolgreiche Umsetzungen sind. Das scheint vor allem dann zuzutreffen, wenn sich Digitalisierungsinitiativen ausschließlich auf den Oberbürgermeister (OB) beschränken und dieser Digitalisierungsziele ohne Einbindung der Dezernatsleitungen, Gemeinderat und Fachbereichsleitungen verfolgt.

3) Unterstützung durch die Verwaltungsspitzen

In Ludwigsburg ist die Verwaltung in vier Dezernate aufgeteilt. Deren Leitungen bilden der OB, die Erste Bürgermeisterin, sowie zwei weitere BürgermeisterInnen. Als Schnittstelle zwischen Kommunalpolitik und Verwaltungsabteilungen sind sie es, die koordinierend in die dem Dezernat zugeordneten Fachbereiche wirken können.

4) Vertrauen

Unterstützung durch den OB und die Verwaltungsspitzen sind auch dadurch geprägt, welches Vertrauen untereinander implementierten Strukturen zur Bearbeitung von Digitalisierung zuteil wird.

Auch wenn der neue Fachbereich in Ludwigsburg noch jung ist, zeichnete sich in den Befragungen ein vertrauensvolleres Verhältnis mit der Leitung ab. Dazu gehört die Bereitschaft, Bedarfe innerhalb der Verwaltung abzufragen und die Kapazität, Strategien entsprechend daran auszurichten. Vertrauen garantiert keine erfolgreiche Digitalisierung, ist aber eine notwendige Bedingung.

5) Querschnittseinheit

Gerade das Querschnittsreferat für nachhaltige Stadtentwicklung hatte in Ludwigsburg für erfolgreiche Projektarbeit gesorgt, ehe es beim Thema Digitalisierung einer Neustrukturierung unterlief. Da digitale Infrastrukturen sich nicht nach Ressortgrenzen richten und ihre Wirksamkeit vor allem vom Maß der Integration geprägt ist, bieten sich Querschnittseinheiten innerhalb der Verwaltungen an, das Thema zu bearbeiten. Manche Kommunen schaffen dafür einen Beauftragten (oder: CDO, CIO, …) und/oder einen eigenen Fachbereich. Das Material legt nahe, dass die Einstellung eines Digitalisierungsbeauftragten (oder eines kleinen Teams) nicht notwendigerweise dieser Querschnittsfunktion gerecht werden kann. Ferner ist die Wirksamkeit davon abhängig, wie das Zusammenspiel mit anderen Abteilungen gestaltet ist. Dieses hängt wiederum vom Vertrauen und der Unterstützung durch Verwaltungsspitzen ab. Auch wenn Rufe nach einem eigenen Fachbereich (oder auf Bundesebene Digitalministerium) häufig zu hören sind, wenn es um Digitalisierung geht, kann es ebenso sinnvoll sein, auf vorhandene Strukturen zurückzugreifen. Dies kann kompetenz- und personalstarke Abteilungen betreffen, deren Arbeit innerhalb der Verwaltung durch Rückhalt und Vertrauen gekennzeichnet sind. Es können ebenso Referate oder andere in der Vergangenheit etablierte Verwaltungsstrukturen sein, die in mehrere Fachbereiche hineinwirken oder in denen Fachbereiche zusammenkommen und bereits Ebenen übergreifend miteinander arbeiten. Ein weiteres Merkmal solcher Querschnittseinheiten kann sein, dass Digitalisierung bereits thematisch bearbeitet wird (beispielsweise durch die Linse eines Referates für Klimaschutz) und nicht als separates, womöglich technisches Handlungsfeld.

6) Integration von Technik und Organisation

Eine große Herausforderung, die bei kommunaler Digitalisierung auftreten kann, ist die Überbetonung der technischen Dimension. Es kann überraschend sein, welche organisatorischen Konsequenzen sich ergeben, sobald vormals analoge Bearbeitungsmomente in Verwaltungsprozessen digital ablaufen sollen. Technische Komponenten und die Organisationsentwicklung sind eng miteinander verwoben. Durch das enge Wechselverhältnis werden bei der Umsetzung digitaler Arbeitsweisen fast unweigerlich unvorhergesehene Herausforderungen auftreten, derer man sich vorher nicht bewusst war. Dies kann die Bedeutung von Arbeitsschritten umfassen, die bislang nie explizit oder verschriftlicht abgelegt wurden, aber eine essenzielle Funktion in der Bearbeitung erfüllen. Dazu kann beispielsweise die Bedeutung von Sichtvermerken und handschriftlichen Notizen für die Übersicht gehören.

Idealerweise findet dieser Umstand Ausdruck in Steuerungseinheiten, die beide Dimensionen abbilden können. Ein Fachbereich für Digitalisierung benötigt enge Schnittstellen zur Organisationsentwicklung oder ist idealerweise auch für diese Themen zuständig. In Ludwigsburg gibt es eine Trennung zwischen dem Fachbereich der Digitalisierung und IT und dem der Organisationsentwicklung und des Personals. Dieser Trennung begegnet man mit projektbasierten Schnittstellen, an denen beide zusammenarbeiten. Wichtig ist jedenfalls vor allem bei Verwaltungsdigitalisierung, die organisationale Dimensionen von Digitalisierung mitdenken und bearbeiten zu können.

7) Vision

Gerade, weil die Stadt von vielfältigen Verständnissen der Digitalisierung betroffen ist, wird es notwendig sein, ein eigenes Arbeitsprogramm zu erstellen, das die lokale Realität aufnehmen und im Rahmen weitergehender städtischer Entwicklungsziele gestalten kann. Gegenwärtig fehlt es noch an einer gesamtstädtischen Vision, die durch die Formulierung eines gemeinsamen Ziels die unterschiedlichen Interessen innerhalb der Verwaltung verbindet. Eine Vision sollte hinreichend konkret sein, um Digitalisierungsaktivitäten an ihr messen und gegebenenfalls neu ausrichten zu können. Eine Vision legt außerdem einen wertebasierten Rahmen vor, an welchem sich einzelne Projekte ausrichten sollten. Idealerweise erzeugt eine Vision gemeinsam getragene Ziele und vereinheitlicht die vielfältigen Digitalisierungsbilder und –zwecke, die inner- und außerhalb der Stadtverwaltung auftreten. Wenn z.B. entscheidungsverantwortliche Beteiligte zum Zwecke der Einsparung Digitalisierung vornehmlich als kommunalfinanzielles Instrument verstehen, andere wiederum den Nutzen für Antragsstellende in den Vordergrund stellen, andere wiederum den Arbeitsaufwand für Mitarbeitende durch standardisierte Aufgaben verringern wollen oder städtische Probleme durch eine neue Datenbasis effektiver bearbeitet sehen, kann es zu einer Konkurrenz dieser unterschiedlichen Ziele, Hoffnungen und Motivationen kommen. Diese kann zur Folge haben, dass beispielsweise bei der Höhe zugewiesener Haushaltsmittel Uneinigkeit herrscht, oder bei der gemeinsamen Arbeit in Gremien oder Lenkungsgruppen Grundsatzdebatten entstehen und nicht ‚alle an einem Strang ziehen'.

8) Personalressourcen

Ein neuer Fachbereich kann nur so effektiv wie sein Personal sein. Kommunen können IT-Fachkräften in der Regel nicht die Konditionen der Privatwirtschaft bieten. Die Rekrutierung von geeignetem Personal setzt ferner voraus, einschätzen zu können, welches Kompetenzprofil für kommunale Digitalisierung erforderlich ist. Personalmangel ist aber auch im Bestand ein großes Thema. In Ludwigsburg wird beispielsweise neben dem alltäglichen Geschäftsbetrieb am digitalen Bauamts-Projekt gearbeitet.

9) Klare Zuständigkeiten

Was auf Bundes- und Landesebene gilt, gilt auch im kommunalen Kontext. Aus den Befragungen ging hervor, dass manche IT-seitigen Entscheidungen, wie beispielsweise die Nutzung eines Videokonferenzprogrammes, für Gemeinderatsmitglieder nicht nachvollziehbar waren. Ebenso gab es Bedarfe, neue Programme und Hardware nicht nur zur Verfügung gestellt zu bekommen, sondern auch Ansprechpersonen bei der Einrichtung zu haben. Diese Situationen können ein Anzeiger für unklare Zuständigkeiten sein, welche in der Verwaltung fragmentiert vorliegen und erst erfragt werden müssen. Wenn digitale Technologien den Arbeitsalltag zunehmend unterstützen und prägen sollen, sind klare Zuständigkeiten bei Rückfragen notwendig. Das gilt ebenso für geplante Digitalisierungsprojekte. Es muss allen Beteiligten klar sein, wer welche Entscheidungen treffen kann und wer für die Umsetzung dieser Entscheidungen schließlich verantwortlich ist.

VI. Zusammenfassung und Ausblick

Ziel des Aufsatzes war die theoriegeleitete Identifikation von empirisch validierten Erfolgsfaktoren der digitalen Transformation kommunaler Verwaltung im Bereich „Digitales Bauamt" auf Basis einer Case Study mit der Stadt Ludwigsburg und Desk Research. Spezifischer wurde ein theoretisch fundierter und empirisch validierter Beitrag dazu geleistet, erste rechtliche, institutionelle, prozessuale und ideative Erfolgsfaktoren der Implementation und Umsetzung des OZG im Rahmen eines Multi-Level Governance Ansatzes vorzulegen.

In der nächsten Projektphase sollen die Limitationen einer Case Study durch eine Erweiterung auf eine small N Studie erweitert werden. Hierzu soll der Roll-Out der Einer für Alle (EfA) Lösung „Digitales Bauamt" aus Mecklenburg-Vorpommern in ausgewählten Kommunen Baden-Württembergs begleitet werden (https://www.digitale-baugenehmigung.de). Dieser Schritt wird es uns ermöglichen, systematische Zusammenhänge zwischen den im Paper skizzierten Spannungsfeldern, Typen von (Mehrebenen-)Governance und der Qualität von kommunalen Digitalisierungsprozessen zu identifizieren. Auf dieser Basis sollen schließlich von den Konsortialpartnern Politikempfehlungen ausgesprochen und Weiterbildungsangebote entwickelt werden.

Danksagung

Die AutorInnen bedanken sich für die Förderung des Projektes „Smarte Systemarchitektur für kommunales E-Government" bei dtec.bw – Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr.

Literatur

[1] C. Schwab, S. Kuhlmann, J. Bogumil und S. Gerber, Digitalisierung der Bürgerämter in Deutschland, Düsseldorf: Hans-Böckler-Stiftung, 2019.

[2] I. Mergel, „Digital Transformation of the German State," in *Public Administration in Gemany*, Cham, Palgrave Macmillan, 2021, pp. 331-356.

[3] S. Kuhlmann und M. Heuberger, „Digital transformation going local: implementation, impacts and constraints from a German perspective," *Puclic Money & Management,* pp. 1-9, 2021.

[4] vhw, 2022. [Online]. Available: https://www.vhw.de/forschung/lokale-demokratie/demokratische-deliberation/projekte/smarte-systemarchitektur-fuer-kommunales-e-government/.

[5] R. Mayntz, „Governance Theory als fortentwickelte Steuerungstheorie?," *MPIfG Working Paper,* 04/01 2004.

[6] J. Kooiman, Governing as governance, London: Sage, 2003.

[7] R. Mayntz und F. W. Scharpf, „Der Ansatz des akteurzentrierten Institutionalismus," in *Gesellschaftliche Selbstregelung und politische Steuerung*, Frankfurt am Main, Campus, 1995, pp. 38-72.

[8] J. Kooiman und M. Bavinck, „The governance perspective," in *Fish for life: interactive governance for fisheries*, Amsterdam, Amsterdam University Press, 2005, pp. 11-24.

[9] H. Heinelt, „Planung und Governance. Der Beitrag der Governance-Debatte zum Planungsverständnis.," in *Zur räumlichen Entwicklung*

beitragen. Planung neu denken, Dortmund, Edition Stadtentwicklung, 2006, pp. 235-247.

[10] J. Gjaltema, R. Biesbroek und K. Termeer, „From government to governance...to meta- governance: a systematic literature review,“ *Public Management Review,* pp. 1760-1780, 12 22 2019.

[11] W. Rammert, „Technik in Aktion: verteiltes Handeln in soziotechnischen Konstellationen.,“ in *Autonome Maschinen*, Weisbaden, Westdeutscher Verlag, 2003, pp. 278-315.

[12] W. Rammert, „Technisierung und Medien in Sozialsystemen. Annäherung an eine Soziologie der Technik,“ in *Technik als sozialer Prozess,*, Frankfurt am Main, Suhrkamp, 1989, pp. 128-173.

[13] D. G. Johnson und J. M. Wetmore, „STS and Ethics: Implications for Engineering Ethics,“ in *The handbook of science and technology studies*, Chicago, MIT Press, 2008, pp. 567-581.

[14] W. Bijker, Of bicycles, bakelites, and bulbs: Toward a theory of sociotechnical change, Cambridge: MIT Press, 1997.

[15] S. L. Star und K. Ruhleder, „Steps Toward an Ecology of Infrastructure: Design and Access for Large Information Spaces,“ *Information Systems Research,* pp. 111-134, 1 7 1996.

[16] W. E. Bijker, „Understanding Technological Culture through a Constructivist View of Science, Technology, and Society,“ in *Visions of STS. Counterpoints in science, technology, and society studies*, Albany, N.Y., State University of New York Press, 2001, pp. 19-34.

[17] W. E. Bijker, P. Volonte und C. Grasseni, „Technoscientific dialogues. Expertise, democracy and technological cultures,“ *TECNOSCIENZA: Italian Journal of Science & Technology Studies,* pp. 121-140, 2 1 2011.

[18] L. Winner, „Do Artifacts Have Politics?,“ *Daedalus,* pp. 121-136, 1 109 1980.

[19] O. Hanseth und J. R. Modol, „The dynamics of architecture-governance configurations: an assemblage theory approach,“ *Journal of the Association for Information Systems,* p. 5, 1 21 2021.

[20] C. J. Woodard, „Architectural control points,“ in *Proc. Third Internat. Conf. Design Sci. Res. Inform. Syst. Tech*, Atlanta, 2008.

[21] P. Muckel, „Die Entwicklung von Kategorien mit der Methode der Grounded Theory,“ *Historical Social Research,,* pp. 211-231, 19 2007.

[22] R. Kurt und R. Herbrik, „Sozialwissenschaftliche Hermeneutik und hermeneutische Wissenssoziologie,“ in *Handbuch Methoden der empirischen Sozialforschung*, Wiesbaden, Springer, 2014, pp. 473-491.

[23] R. Andres, J. Andres, P. Breithaupt, R. Janßen, E. Kollmann, T. Niebel, S. Reif und M. Seifried, Metastudie: Chancen und Herausforderungen der Digitalisierung in Baden-Württemberg, Mannheim: ZEW-Gutachten und Forschungsberichte, 2021.

[24] H. H. Lühr, „IT-Planungsrat,“ in *Handbuch Digitalisierung in Staat und Verwaltung*, Wiesbaden, Springer, 2020, pp. 1-12.

[25] IT-Planungsrat, „Digitalisierungsprogramm OZG Bund – Reifegradmodell. Version 1.1,“ 2020. [Online]. Available: https://www.it-planungsrat.de/fileadmin/beschluesse/2020/Beschluss2020-20_Reifegradmodell.pdf . [Zugriff am 1 9 2022].

[26] O. Hanseth, E. Monteiro und M. Hatling, „eveloping information infrastructure: The tension between standardization and flexibility,“ *Science, Technology, & Human Values,* pp. 407-426, 4 21 1998.

[27] f. B. u. H. Föderale IT-Kommission & Bundesministerium des Innern, „Programmmanagement Digitalisierungsprogramm Phase 2,“ 2020. [Online]. Available: https://ozg.brandenburg.de/4f777d7e1a882f40662afb3f326af32a7fe2566a/5f4ba4a0-729b-9b5e-c13c-a8687ca1169d/tap2_cHZu0X_dec/OZG_Programmmanagement-Phase%202_v3.0-1.pdf. [Zugriff am 1 9 2022].

[28] D. Tilson, K. Lyytinen und C. Sørensen, „Research commentary—Digital infrastructures: The missing IS research agenda,“ *Information systems research,,* pp. 748-759, 4 21 2010.

[29] G. C. Bowker, K. Baker, F. Millerand und D. Ribes, „oward information infrastructure studies: Ways of knowing in a networked environment,“ in *International handbook of internet research*, Dordrecht, Springer, 2010, pp. 97-117.

[30] J. S. Brennen und D. Kreiss, „Digitalization,“ in *The International Encyclopedia of Communication Theory and Philosophy*, Chichester, Wiley, 2016, pp. 1-11.

[31] F. Stalder, „Herausforderungen der Digitalität jenseits der Technologie,“ *Synergie–Fachmagazin für Digitalisierung in der Lehre,* Bd. 5, pp. 8-15, 2018.

[32] D. Fleuß, G. S. Schaal und K. Helbig, „Empirische Messung digitalisierter Demokratien: Erkenntnistheoretische Herausforderungen und eine wissenschaftstheoretische Antwort,“ *Politische Vierteljahresschrift,* pp. 461-486, 3 60 2019.

[33] S. L. Star und G. C. Bowker, „How to Infrastructure,“ in *Handbook of New Media: Social Shaping and Social Consequences of ICTs*, London, Sage, 2006, pp. 230-245.

[34] H. M. Collins, Artificial Experts: Social Knowledge and Intelligent Machines, Cambridge: MIt Press, 1990.

[35] H. M. Collins, Tacit and explicit knowledge, Chicago: University of Chicago Press, 2010.

[36] M. Hodson, J. Kasmire, A. McMeekin, J. G. Stehlin und K. Ward, Urban platforms and the future city: Transformations in infrastructure, governance, knowledge and everyday life, London: Routledge, 2020.

[37] M. Altenried, S. Animento und M. Bojadžijev, „lattform-Urbanismus: Arbeit, Migration und die Transformation des urbanen Raums,“ *sub\urban. zeitschrift für kritische stadtforschung,* pp. 73-91, 12 9 2021.

[38] R. G. Hollands, „Will the real smart city please stand up? Intelligent, progressive or entrepreneurial?,“ in *The Routledge companion to smart cities*, London, Routledge, 2020, pp. 179-199.

[39] J. C. Scott, Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed, New Haven and London: Yale University Press, 1998.

[40] M. Polanyi, „The tacit dimension,“ in *Knowledge in organizations*, London, Routledge, 2009, pp. 135-146.

[41] V. Hepsø, E. Monteiro und K. H. Rolland, „Ecologies of e-Infrastructures,“ *Journal of the Association for Information Systems,* p. 2, 5 10 2009.

[42] Q. A. f. Forschung, „https://www.teamq.de,“ 2022. [Online].

The Socio-Economic Panel Linked Employer-Employee Survey Version 2 (SOEP-LEE2): Overview and Results from the First Wave

Wenzel Matiaske*, Torben Dall Schmidt, Christoph Halbmeier, Martina Maas
Helmut Schmidt University / University of the Federal Armed Forces Hamburg
Hamburg, Germany
*matiaske@hsu-hh.de

Carsten Schröder*, Tamara Böhm, Alexander S. Kritikos, Stefan Liebig
German Institute for Economic Research (DIW Berlin)
Berlin, Germany
*cschroeder@diw.de

***Abstract* – The trend toward digitalization not only changes the organization of work in areas such as production, services and logistics, but also the work situation of employees. To study such changes, data is needed at both the individual and corporate levels. The SOEP-LEE2 project contributes to research through a linked employer-employee study in combination with an establishment and self-employed survey for Germany. The data infrastructure enables research into the organizational characteristics (such as ownership, turnover, employment structure), human resource management, changes in the organization of work and the consequences for the employees and their households. The data infrastructure relates this to different aspects of digitalization. In this article we describe the research project with the different surveys and present some results based on the first wave.**

Keyword – Linked Employer-Employee Data, Digitalization, COVID- 19, SOEP, Human Resource Management

NOMENCLATURE

COVID-19	Coronavirus disease
FDZ	Research data center
IAB	Institute for Employment Research
INFAS	Institute for Applied Social Science GmbH
SOEP	Socio-Economic Panel

I. INTRODUCTION

The sociological observation of changes in the organization of work, not only as a result of digitalization, requires data at various levels. The change has preconditions on the part of the individuals, e.g. with regard to education, career or life situation, and has consequences for these variables. Parallel to this, the company level, in particular the organization of work, but also personnel management and personnel development, must be considered. If one assumes that this change is incremental, continuous observation of the link between both levels—individuals and companies—is required [1], [2]. Linked employer-employee data sets are regularly called for in the literature. However, this demand is not met, as the production of such data sets is not only costly, but ideally also requires linking with existing social science instruments and data sets.

The SOEP-LEE2 project fills this gap. Based on a central data set for continuous observation at household and individual level in Germany, the project taps into additional data sources to supplement the description of the work situation of the employed surveyed in the Socio-Economic Panel (SOEP). The SOEP has been collecting data at the household and individual level annually for almost 40 years. Following on from a first attempt [3], the project serves to establish the survey of establishments of employed persons in the SOEP. Self-employed persons are asked separately about their company or—as solo self-employed persons—individual work situation. Finally, the project includes comparative surveys of establishments on the basis of the IAB establishment register in order to be able to assess methodological aspects of the employer-employee linked survey instrument, which is still little tested in Germany. Insofar as the data sets produced are made available to the secondary analyses, SOEP-LEE2 can be seen as a contribution to the establishing the national research data infrastructure. It therein builds on well-established data structures (SOEP) extending these into an employer-employee linked setting.

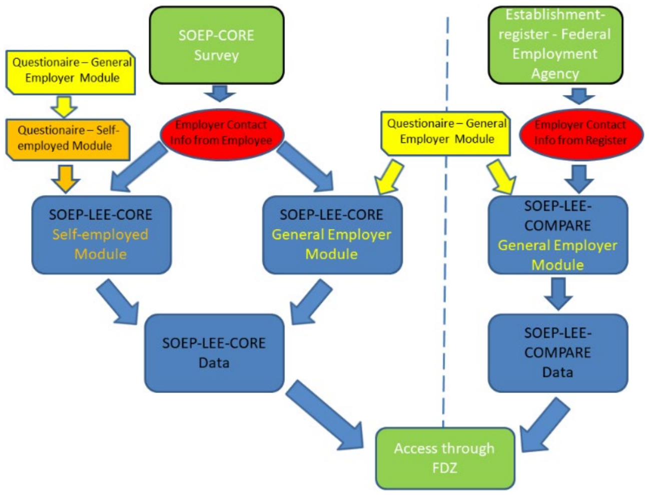
The following sections first outline the project structure and the various data collections over time (II). We then focus on the first wave of the linked employer-employee dataset (III) and its statistical description (IV). In the following section (V) we sketch the next steps of data analysis, processing and release for secondary analytical research and conclude with a summary (VI).

II. THE SOEP-LEE2 PROJECT

The SOEP-LEE2 project is an interdisciplinary research data infrastructure project that combined different existing and new surveys. The data infrastructure comprises three different surveys: 1. SOEP-LEE2-CORE, 2. SOEP-LEE2-COMPARE and 3. SOEP-LEE2-SELF-EMPLOYMENT. The SOEP-

https://doi.org/10.24405/14580

LEE2-CORE survey is an employer-employee linked survey with an employee-first design. This means that employees are first interviewed in the SOEP survey about employer contact data and employers are subsequently surveyed. The survey data on the employees from SOEP is linked to survey data on their employer, which makes it possible to examine the work situation of employees in the SOEP in more detail. Because of the variable-rich data sets at the individual and organizational levels, a wide variety of research questions can be investigated. The SOEP-LEE2-CORE survey has two waves with the first wave being just completed in July 2022, while a second wave will arrive in 2024. In contrast, the SOEP-LEE2-COMPARE survey will be conducted annually from 2022 to 2024. This survey is a representative establishment survey based on the establishment register of the German Federal Employment Agency at IAB. The sample of the SOEP-LEE2-COMPARE is stratified by 5 strata of firm sizes, 8 strata of business sectors and 2 strata of geography. This survey allows for representative studies at the establishment level. Furthermore, the questionnaires of the SOEP-LEE2-CORE and the SOEP-LEE2-COMPARE survey are identical. The consequences of using an employer-first design in the SOEP-LEE2-CORE data in terms of for example nonresponse can accordingly be researched in detail. The SOEP-LEE2-SELF-EMPLOYMENT is an additional survey of the self-employed persons in the SOEP sample. For this survey, a special module for self-employed persons is created addressing issues for self-employed based on the establishment survey of the SOEP-LEES-CORE. This makes it possible to compare the situation for self-employed persons with the situation in other types of establishments. This survey arrives in 2022 and 2024.



FIGURES 1: CONCEPTUAL FRAMEWORK FOR THE SOEP-LEE2 DATA STRUCTURE.

The questionnaires of the first wave of SOEP-LEE2-CORE and SOEP-LEE2-COMPARE have the same topics. This includes questions about company characteristics, as well as questions about human resource management, wage and digitalization. A main focus is on the effects of COVID-19 and the reactions of the companies, especially on the implementation and development of remote work and digital solutions. The questionnaire has 64 questions. The survey is conducted by the external survey institute INFAS (Institute for Applied Social Science GmbH).

III. DESIGN AND PARTICIPATION RATES OF THE FIRST WAVE OF THE LINKED EMPLOYER-EMPLOYEE SURVEY (SOEP-LEE2-CORE)

At the time of writing, data collection for the first wave of the linked employer-employee (SOEP-LEE2-CORE) survey has completed, which allows us to give a brief overview of the survey design and the response rates. As described above, the design of the SOEP-LEE2-CORE survey relies on the employee-first method. This approach requires an ideally representative sample of employees who are willing to provide the name and further contact details of their employer. Here, we use the 2021 wave of the SOEP-Core survey (SOEP hereafter), which asks for employer contact information (see section III.A). In a next step, the contact information is used to reach and survey the employers (section III.B). Together, the two surveys constitute SOEP-LEE2-CORE.

A. Employee Survey (SOEP-Core 2021)

In SOEP-LEE2, the representative sample of employees consists of all employees of the 2021 wave of SOEP. The SOEP is a yearly panel survey that is representative for private households living in Germany. It is a suitable basis for the goals of the SOEP-LEE2 project for a set of different reasons. The SOEP survey collects individual information from each household member, providing a representative sample of individuals living in Germany. Second, the number of survey respondents is relatively large. Typically, a wave of the SOEP comprises around 30,000 individuals, although the number has somewhat diminished in 2021 [4]. The large size of the initial sample mitigates the effects of an inevitable reduction in the sample size along the sampling process of the employee-first method (see below). Lastly, due to a panel design and extensive questionnaires, the SOEP contains rich data relevant for the SOEP-LEE2 project, such as detailed records on income, education, and employment, measures of physical, and mental health, and information on the household context.

In the 2021 wave, employees in the SOEP were additionally surveyed for the name and address of their current employer. The question text specifically asked for contact information of a company's local branch or subsidiary to ensure that data on the immediate workplace environment could be collected in the subsequent employer survey. Moreover, the question was accompanied by a transparency statement informing respondents that the collected data would be used, first, to conduct a survey with employers, and second, to link public register employer data to the survey data.

Response rates to the questions on employer contact information are presented in TABLE I (preliminary data). Response was generally high. From a total of 8920 employees, 73.2 percent reported the name of their employer, with rates being similar for the different elements of an employer's address. First analysis of the response process shows that employees of large companies and employees working in the public sector are somewhat more likely to name their employer [5]. Overall however, the relatively high response rate suggests that (non-)response to the question on employer contact information probably produces relatively little selection bias in the sample.

TABLE I: RESPONSE RATES TO QUESTIONS ON EMPLOYER CONTACT INFORMATION IN SOEP-CORE 2021 (PRELIMINARY DATA).

	N	*Percent*
SOEP employees (w/o migrations samples M3-M8)	8920	100
Respondent provided:		
- Name of employer	6525	73.2
- Municipality	6518	73.1
- Postal code	6127	68.7
- Street	6164	69.1
- House number	5865	65.8
- Name and complete address	6093	63.4

B. *Establishment Survey (SOEP-LEE2-CORE)*

After completion the SOEP survey, data collection for the linked establishment survey began. Establishments were surveyed between November 2021 and June 2022, with the majority of interviews being conducted during the first quarter of 2022. Relative to the planned schedule, data collection for the establishment survey was delayed by about half a year due to a postponement of the 2021 wave of the SOEP survey in the course of the COVID-19 pandemic.

The survey institute offered different survey modes to accommodate the needs of the respondents, and aiming to achieve high response rates. While the first contact was established by telephone, respondents could choose to conduct the interview by telephone, web, or self-administered pen-and-paper questionnaires. Around half of the respondents in the first wave opted for a telephone interview, 45 percent for a web interview, and five percent chose self-administered pen-and-paper questionnaires.

The survey institute contacted a total of 5204 establishments, of which 990 (19 percent) agreed to participate in the interview. Of these, 732 establishments completed the interview, resulting in a response rate of 14 percent. The rate is lower than that of, for example, the establishment panel of the Institute for Employment Research (IAB), which in recent years has attained response rates of 32 to 35 percent in samples of newly-recruited German establishments. Different from the SOEP-LEE2 survey, the IAB establishment panel relies on face-to-face interviews and might be better known among firms due to its longer existence, which may explain some of the discrepancies in response rates [6].

IV. DESCRIPTIVE ESTABLISHMENT CHARACTERISTICS FROM THE FIRST SURVEY WAVE

The data collected from the first wave of the establishment survey allow us to characterize the participating establishments and to identify first relevant patterns in their responses. The description also provides a good overview of the four main topics covered by the survey: (1) General establishment characteristics and the workplace environment, (2) digitalization, (3) organization of work, personnel management and development, and (4) the COVID-19 pandemic.

A. *General Establishment Characteristics and the Workplace Environment*

To begin with, it is instructive to summarize some general characteristics of the participating establishments. Most of the 732 establishments that completed the interview are from the private sector (64.9 percent), while the other third is publicly owned. On average, the establishments have 667 employees, with a more detailed breakdown of establishment by size given in TABLE II. The majority of establishments in the sample employ between 10 and 49 persons or between 50 and 249 persons. Very few establishments have fewer than five employees, as very small establishments were excluded from the SOEP-LEE2-CORE survey for privacy concerns and based on a priori information on the establishment size.

TABLE II: CHARACTERISTICS OF THE SURVEYED ESTABLISHMENTS, UNWEIGHTED STATISTICS.

Characteristics	*Percent*
Number of employees:	
- 0–4	1.85
- 5–9	6.41
- 10–49	31.3
- 50–249	32.8
- 250–499	11.0
- More than 500	16.7
Sector:	
- Private	64.9
- Public	35.1
Composition of workforce	
- Average percentage of female workforce	54.5
- Average percentage of foreign workforce	8.2
- Average percentage of workforce in occupations that do not require apprenticeship	14.8
- Average percentage of workforce in occupations that require apprenticeship or comparable professional experience	56.2
- Average percentage of workforce in occupations that require degree from university (of applied sciences)	30.9

The data also contain information about the work environment, such as the composition of the workforce. Those aspects are not only interesting to analyze processes at the establishment level, but they also characterize the work environment individuals are exposed to. As such, we expect them to have an effect on individual career opportunities, job-related decision-making, and individual attitudes and beliefs. While the analysis of these effects is part of future research, we can present some aggregated statistics at the establishment level. On average, 54.5 percent of the workforce in surveyed establishments are female, and the average share of the workforce with foreign background is 8.2 percent. Moreover, the average workforce consists of 14.8 percent employees in occupations that do not require apprenticeship. On the other hand, the average share of the workforce in occupations that do require apprenticeship is 56.2 percent, and for those occupations that require a university degree it is 30.9 percent.

These numbers indicate that the establishments in the sample rely on a highly educated workforce.

B. Digitalization

Digitalization is one of the far-reaching processes that are expected to continuously transform the way companies operate and organize their workforce. As such, the topic assumes a prominent role in the SOEP-LEE2-CORE survey. For example, as a general indicator of digitalization, the survey asks for the usage of computers, laptops, and digital devices for task completion at work. On average, 69.1 percent of an establishment's employees use these devices, indicating that, digital devices are, maybe not surprisingly, a very common tool for task completion, even if a significant share of workers still do not apply them. Further questions on more specific types of technology highlight that over the last years the majority of establishments has intensified the usage of different digitalization technologies, emphasizing the ubiquity and relevance of digitalization at the workplace.

The effects and drivers of digitalization are one of the relevant research topics addressed in the SOEP-LEE2 project. First descriptive results from the first wave of the survey already show some important aspects to consider from the viewpoint of establishments. For example, 54.4 percent of the surveyed establishments agree with the statement that digital technologies led to an increased need for employee training and education. Similarly, 45.5 percent of the establishments state that the usage of digital technologies causes a strong dependency on external service providers, all of which suggests that digital technologies render the production process more complex and demanding. On the other hand, the results show that only a small share of establishments (15.1 percent) agrees with the statement that their employees tend to be critical of digitalization technologies. This suggests that employee attitudes are unlikely to be a barrier to expanding the use of digital technologies in the future.

C. Organization of Work, Personnel Management and Development

The (re-)organization of work, personnel management, and the educational development of the workforce are ways in which establishments potentially respond to digitalization and sociological changes. In the SOEP-LEE2-CORE survey, the corresponding questions first ask for current challenges in personnel management to identify areas where establishments see urgency to act. Descriptive results show that for a large majority of establishments (72.5 percent) it is a large or very large challenge to recruit the required number of qualified employees. Similarly, 46.8 percent see general personnel shortages as a problem. Moreover, 52.6 percent of the establishments are confronted with a heavy workload for the existing staff, which possibly reflects the unmet demand for workers. In contrast, somewhat less of a challenge are high salary costs (26.2 percent see it as a large or very large challenge), an ageing workforce (19.1 percent), a large need for training of the workforce (18.0 percent), and a high employee turnover rate (14.7 percent).

In light of these challenges, establishments may invest more into human capital, for example by increasing their efforts to recruit new employees or train the workforce. In the SOEP-LEE2-CORE survey, establishments are asked how they organize their human resource management and whether they use certain types of recruitment methods and employee training. The questions distinguish between employee skill group to assess how human capital investments are allocated over the skill distribution. With respect to training, first results show that almost every establishment in the sample (96.6 percent) offers some form of employee training, including on-the-job training. However, the likelihood of such offers differs depending on the skill group. Workers in the lowest skill group, that is employees in occupations that do not require apprenticeship, are less likely to get the opportunity for training. Among those establishments that employ low-skilled workers, 81.9 percent offer training for this skill level of workers. This is less than the 93.6 and 95.1 percent of establishments that employ and offer training for the middle and upper skill groups. There are also differences in the type of training offered. For instance, establishments are less likely to offer courses or seminars to low-skilled workers (66.9 percent, conditional on offering training to this group), compared to middle-skilled (87.9 percent) or high-skilled workers (89.9 percent), suggesting that investments into human capital are somewhat more directed towards those workers with a skill advantage.

D. COVID-19 Pandemic

The COVID-19 pandemic is another of the four main topics of the first wave of the SOEP-LEE2 establishment survey. The survey focusses on the pandemic's impact on the size of the workforce, on hiring and layoffs, the number of working hours, and the usage of remote work. Establishments are asked to compare their pre-pandemic situation to that of the first half of 2021, when Germany was hit by the third wave of the pandemic and different lockdown measures were temporarily in place, including the closure and restriction of certain types of businesses, and the requirement to work remotely from home if possible [7].

The pandemic and its lockdown measures show in the data. With respect to the working hours, descriptive results suggest that establishments were relatively likely to reduce working hours in response to the COVID-19 pandemic. In total, 59.7 percent of the establishments took measures to cut down the number of hours worked. Establishments most commonly opted for a reduction of accumulated working time credits or an increase in debit hours in their employees' working time accounts (52.1 percent), followed by an introduction of short-time work (27.6 percent), and a mandated use of vacation days (24.2 percent).

Unlike working hours, most establishments did not adjust the size of their workforce. The data indicate that 58.7 percent of establishments in the sample employed the same number of persons as before the pandemic. And only 16.6 percent of the establishments report a decrease in the number of employees. Additional questions on whether establishments responded to the pandemic by adopting specific human resource policies confirm the overall impression. Most establishments (70.6 percent) did not implement any of the policies surveyed that aimed at a reduction of the workforce size. The most commonly adopted measures were to postpone a planned increase of the workforce (17.3 percent) and not filling vacancies (15.1 percent), suggesting that establishments made only moderate adjustments to the size of the workforce, and if so, by a hiring freeze.

A clear response to the pandemic is evident with respect to remote work. In mid-2021, 67.3 percent of the establishments in the sample had part of their workforce working from home. In most of these establishments (92.0 percent), the share of employees working remotely increased during the COVID-19 pandemic, emphasizing the pandemic's large impact on the organization of work. In addition, the data show that the establishments grant their employees a certain flexibility as regards to when they work from home. In 69.6 percent of establishments where remote work is available, employees decide jointly with the employer on the times when they work remotely. In the remaining establishments, the decision is taken either mostly or exclusively by the employer (18.4 percent) or the employees (12.1 percent).

V. Upcoming research agenda

The central task is the preparation and provision of the data sets in the research infrastructure. This includes quality assurance [8] and in particular the analysis of the non-response in order to be able to assess possible biases. The design of the project comprising comparable questionnaires in particularly SOEP-LEE2-CORE and SOEP-LEE2-COMPARE offers unique opportunities along those lines. For these analyses the project also cooperates with the IAB Establishment Panel, which has access to supplementary data in context of the comparison sample. Beyond the research on survey methodology, the analyses focus on the development of a typology of human resource management and industrial relations. Analyses of the use and impact of digital technologies are also planned. This includes analyses of the spread of various forms of remote work [9]. Aspects of innovation management will also be addressed. Special focus is on questions of social security for the self-employed based on SOEP-LEE2- SELF-EMPLOYMENT.

VI. Conclusion

Social science research, as well as labor and social policy, calls for continuous monitoring of changes in working conditions and labor relations, both at the level of employees and at the level of employers. The SOEP-LEE2 project collects information on establishments and their economic situation, on organization and personnel policy, and on work conditions, based on the address data of the employers of the dependent employees surveyed annually in the SOEP. The focus is on transformation trends due to digitalization in general and the COVID-19 crisis in particular. Using the employee-first methodology, the data on dependent employees in the SOEP are thus enriched by an external data source. Furthermore, the project surveys the self-employed, whereby social security issues are also addressed. In order to be able to control for the methodological effects of the employee first approach, a comparative sample of establishments is surveyed on a representative basis.

The data sets will be processed in the project and made available to the research community via the FDZ. Beyond the project's special research issues, a wide range of research questions will be addressed, not least because of the linkage of data at the individual and company level. It is to be hoped that this contribution to the national data infrastructure will be widely received and will enrich social science research on working conditions and industrial relations in the long term.

Acknowledgement

This Paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project Socio-Economic Panel Linked Employer-Employee Data Version 2 (SOEP-LEE2)].

References

[1] S. Kirchner und W. Matiaske, „Digitalisierung und Arbeitsbeziehungen in betrieblichen Arbeitswelten: Zwischen revolutionärem Wandel und digitalem Inkrementalismus," *Industrielle Beziehungen,* Bd. 26, Nr. 2, pp. 125-129, 2019.

[2] S. Kirchner und W. Matiaske, „Plattformökonomie und Arbeitsbeziehungen: Digitalisierung zwischen imaginierter Zukunft und empirischer Gegenwart," *Industrielle Beziehungen,* Bd. 27, Nr. 2, pp. 105-119, 2020.

[3] M. Weinhardt, A. Meyermann, S. Liebig und J. Schupp, „The Linked Employer–Employee Study of the Socio-Economic Panel (SOEP-LEE): Content, Design and Research Potential," *Jahrbücher für Nationalökonomie und Statistik,* Bd. 237, Nr. 5, pp. 457-467, 2017.

[4] J. Goebel, M. M. Grabka, S. Liebig, M. Kroh, D. Richter, C. Schröder und J. Schupp, „The German Socio-Economic Panel (SOEP)," *Jahrbücher für Nationalökonomie und Statistik,* Bd. 239, Nr. 2, pp. 345-360, 2019.

[5] W. Matiaske, T. Dall Schmidt, C. Halbmeier und M. Maas, „Nonresponse in Organizational Surveys: Evidence from the German Socio-Economic Panel Linked Employer-Employee Survey (SOEP-LEE2)," *mimeo,* p. 25, 2022.

[6] C. König, J. W. Sakshaug, J. Stegmaier und S. Kohaut, „Trends in Establishment Survey Nonresponse Rates and Nonresponse Bias: Evidence from the 2001-2017 IAB Establishment Panel," *Journal of Official Statistics,* Bd. 37, Nr. 4, p. 931–953, 2021.

[7] Mitglieder des Sachverständigenausschusses, „Evaluation der Rechtsgrundlage und Maßnahmen der Pandemiepolitik. Bericht des Sachverständigenausschusses nach § 5 Abs. 9 IFSG," Bundesgesundheitsministerium, Berlin, 2022.

[8] R. M. Groves und L. E. Lyberg, „Total Survey Error: Past, Present, and Futur," *Public Opinion Quarterly,* Bd. 74, Nr. 5, p. 849–879, 2010.

[9] T. Dall Schmidt, W. Matiaske, M. Maas und C. Halbmeier, *Urban surpluses or deficits in the use of home office among German firms,* Pecs, Hungary: Presentation at the ERSA 2022 Conference, 2022.

gefördert durch

dtec.bw

Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr

dtecbw.de

Druckversion: ISBN 978-3-86818-316-0 · Digitale Version: ISBN 978-3-86818-315-3

DOI: https://doi.org/10.24405/14522