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1 | Introduction

This paper intends to further understanding of catastrophic events by reviewing the economic literature on their effects as well as potential means of dealing with the corresponding risks and uncertainties. Since 2000, the world has seen a number of catastrophes including terrorist attacks in the United States and Europe, tsunamis in Southeast Asia and Japan as well as volcanic eruptions in Iceland. All of these have had significant impacts on human well-being and economic activity beyond the regional level. In an increasingly populous and globalized world, these types of events and their repercussions are likely to increase. Hence, it is important to ensure that government and private entities cooperate in an attempt to reduce risks of catastrophes.

Generally, two types of catastrophes are distinguished: man-made and natural. Table A1 shows a list of recent natural disasters with estimated insurance damages. Man-made catastrophes can result from terrorism, crime or human error. While the nature of the damages does not differ substantially, these types of catastrophes require different counter-measures.

The reason for these events' destructive potential lies in the increasing interconnectedness of modern societies and economies. This culminates in so-called critical infrastructure, which is defined by the European Commission (2004) as follows: "Critical infrastructures consist of those physical and information technology facilities, networks, services and assets which, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments in the member states." Mutual dependence can thus set of cascading effects, which can further aggravate damages. As an example, a failure of a power plant is likely to have knock-on effects on customers and potentially suppliers.

The exploration of these effects and the corresponding risks is the aim of the paper. Thus, Section 2 will outline three kinds of effects resulting from catastrophic events. These are the direct, indirect short-term and indirect long-term effects. The focus will be on real, rather than monetary outcomes. In Section 3, the options available to private actors in reducing or hedging catastrophes risks are outlined. These consist of prevention and pro-active measures on the one hand and insurance or risk hedging on the other hand. Section 4 outlines the options available to governments and assesses policies aimed at addressing market failures in the security market. Finally, Section 5 will conclude this review of the existing literature.

2 | Economy-wide effects of catastrophes

2.1 | Direct effects: physical destruction and losses of human life

As an immediate economic impact of any large-scale disaster, one has to recognize the loss of physical assets and human life occurring instantly or in the course of rescue operations. In a macroeconomic view, destruction of any form of physical capital (i.e. non-financial wealth) represents a reduction of the economy's productive capacity. In evaluating the adverse consequences of such a productivity shock, the value of all resource destroyed needs to be expressed in terms of a single monetary measure. With respect to privately owned assets, observed market prices are principally suitable for this task, provided that they sufficiently reflect future revenue flows resulting from a productive usage.[1] Assessing the value of public infrastructure can be much more challenging, especially when it displays features of pure public goods (like motorways, bridges). These goods are provided either free of charge or at highly regulated prices. Hence, it is largely impossible to make statements on losses based on the costs of use. For this reason, indirect methods measuring the extent of business interruptions caused by the infrastructure breakdown are often made use of (Rose, 2004). In case of transport infrastructure, loss estimates should both account for the inability to make shipments and the travel time value of commuters (Gordon et al., 1998).

Even more challenging is an economic assessment of the loss of a human life. A common approach is to draw an analogy to physical assets and estimate the future flow of foregone lifetime earnings (Rice et al., 1967). For instance, in an examination of the costs of the September 11 attacks in New York 2001, Bram et al. (2002) calculate the loss of total earnings of all victims killed by adding up their current annual incomes from 2001 onwards to the year they would have retired. The resulting sum of 7.8 billion USD is considered a proxy for the loss of human capital. This was simply added to the loss of physical capital (21.6 billion USD) to arrive at a measure of 29.4 billion USD for the entire loss.

Empirical evidence on damage determinants

Concerning the determinants of this direct damage, a strand of empirical literature tries to identify linkages to the level of macroeconomic development. One central observation is that developing countries tend to incur bigger monetary damages from catastrophes relative to their GDP than developed countries (Rasmussen, 2004; Loayza

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[1] See Rose (2004) for a discussion of this issue.

et al., 2012). However, significance and direction of a potential causal effect are a priori unclear. For this reason, researchers started to regress meaningful damage measures (typically either number of deaths or monetary damage as a share of GDP [2]) on a range of macroeconomic indicators. Since both economic development and vulnerability towards large-scale threats are linked to geography[3], heterogeneity between countries needs to be controlled for, commonly by means of a Panel Data model. In this vein, Burton et al. (1993) were the first to detect a modestly negative impact of GDP per capita on the death toll from natural disasters, suggesting indeed a linkage to economic development. An obvious explanation would be that richer countries can afford to delegate more resources both to protective measures and to subsequent rescue operations. This result is confirmed by later works such as Kahn (2005) and Toya & Skidmore (2007). Raschky (2008) seeks to test whether this relationship is linear or not. He finds evidence for nonlinearity in the form that the effect diminishes with increasing level of GDP, implying that economic progress cannot reduce damages indefinitely.

Further attention has been devoted to a potential role of institutions. Kahn (2005) finds a negative impact of a nation's level of democracy on the number of deaths associated with a disaster, even when controlling for GDP. The author argues that the presence of democratic institutions lowers the overall level of corruption in the economy, thus preventing the misuse of resources designated to be invested in protective measures. Similarly, Raschky (2008) detects evidence for a similar influence of both government stability and investment climate. These factors might also be interpreted as proxies for the efficiency of damage prevention and mitigation. Skidmore & Toya (2007) go one step further by even integrating educational attainment (measured in average years of schooling) as an additional explanatory variable into damage estimation. Higher educational attainment is also shown to reduce average losses, possibly because the knowledge gain allows individuals to make more wise decisions on prevention.

Finally, Anbarci et al. (2005) shed light on the impact of distributional concerns on damage exposure. They show that not only a country's total level of income, but also the degree of economic inequality matters. Among similarly developed countries, those that exhibit a lower degree of inequality[4] also exhibit a lower average level of fatalities from earthquakes. This is attributed to the role of inequality for incentives to undertake collective action, especially in developing countries. As Freeman et al. (2003)

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[2] In most studies, data is taken from the OFDA/CRED International Disaster Database collected by the Center for Research on the Epidemiology of Disasters (CRED) in Brussels.

[3] For instance, Heger et al. (2008) point out that small islands are especially vulnerable, given their strong dependence on the sensitive sectors agriculture and tourism.

[4] The inequality measure applied by Anbaci et al. (2005) is the Gini coefficient for the ownership distribution of agricultural land.

note for the situation of least developed countries, it's typically the poorest individuals which are the most vulnerable, as they cannot afford the higher prices of land in less disaster-prone areas. On the other hand, the richest individuals have low incentives to contribute to collective protection, given their lower exposure and their higher capability to protect themselves. Very unequal societies thus tend to be unable to come to a satisfying agreement on collective spending, which implies a high degree of vulnerability for a significant part of the population.

2.2 | Indirect short-term effects: supply chain disruptions and recovery measures

The economic loss associated with physical destruction alone can be devastating enough, but economists have also drawn attention to the less visible costs of catastrophes. Most importantly, indirect costs can result from a temporary drop in the productive capacities of firms in disaster-struck areas. In the wake of a large-scale disaster, production can be subject to capacity declines for several reasons: damage done to buildings and machinery, impassability of transport routes, the priority of rescue operations or simply failure of communication and general confusion. This can not only impair the profits of firms facing these capacity constraints, but also the profits of their commercial partners. Interruptions in the supply of intermediate goods to downstream producers will force them to change their production schedules as well. If this concerns essential inputs, it might even render them unable to fulfill their own sales contracts. In addition, if a capacity decline initiates a cutback in production, it could lower the demand for intermediate inputs by affected firms. Hence, upstream producers might also experience a decrease in sales. Given that these upstream producers are again buyers of some external inputs, the shock is still further transmitted to their suppliers. In this way, a supply shock initially focused on just a subset of sectors can spill over to other sectors along the supply chain and eventually harm the whole economy via the channel of external input requirements.

These second-order effects are especially pronounced when they involve the interruption of lifeline services such as electricity and gas, which disturb business operations in all sectors simultaneously. Business surveys such as Tierney (1995) and Dahlhamer & Tierney (1998) indicate that disaster-induced business closures can to a much larger extent be traced back to indirect effects like lifeline outages than to immediate physical damage. Precisely, Alesch et al. (1993) and Tierney (1995) find that small firms are particularly vulnerable to supply chain disruptions, possibly due to their heavier dependence on external inputs.

Analyzing the extent of business interruptions: Input-Output Analysis

To analyze the vulnerability of the aggregate economy, Input-Output Analysis and its extensions represent the methodology most favored by both economists and engineers (Haimes & Jiang, 2001; Rose & Liao, 2005; Hallegatte, 2008). By modeling the whole set of input-output relations between sectors as one system of linear equations, estimates of the impact of any (real or counterfactual) disaster-driven shock on sector production can be derived. Since these estimates are based on equilibrium outcomes, they account for the whole complexity of contagion effects. Therefore, they can offer additional insights compared to alternative strategies like econometric analysis, which primarily rest on ex-post comparisons of the economies aggregates before and after the occurrence of a catastrophe. Moreover, Input-Output Analysis allows researchers to extend the geographical dimension of damage estimation. Neighboring regions of a disaster-struck area, while physically unaffected, might still experience an economic slowdown due to trade-based linkages. Price increases resulting from adverse supply shocks propagate via exports to consumers in other areas, lowering their real income as well.[5]

Another factor contributing to the dissemination of this method is its relative ease of application. In the most basic setting, parameter calibration only requires national account information. The downside of this, however, is the restrictiveness. With respect to disaster research, the most serious shortcoming in this regard is the lack of behavioral flexibility: input shares are assumed to remain fixed; consumer demand is treated as exogenous[6]. As a consequence, estimated damages based on the standard Input-Output method can potentially exhibit a considerable upward bias, as they do not reflect the natural resilience of the economy.

Accounting for channels of damage mitigation

Following Rose (2004), we define economic resilience as the set of all responses to catastrophes that limit the damage done or fasten the economy's recovery.[7] These responses can take place at different levels, including single individuals, households, firms, governments and even institutions (like changes in the price formation on markets). In this, a key factor is the substitutability of goods. As a response to temporary shortages of certain commodities and services, consumers could switch to substitutes, thereby relieving market pressure. Firms could try to compensate the breakdown of some machinery by increasing the workload of their employees. Other forms of resili-

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[5] In estimating losses from a range of worldwide disasters by means of a CGE model, Sahin (2011) shows that accounting for these rippling effects produces significantly larger estimates of total damages than by just considering the sum of individual country losses.

[6] For a detailed discussion of the Pros and Cons of using Input-Output-Analysis in damage estimation, see Kowalewski (2009).

[7] Note that other authors like Bruneau et al. (2003) also include ex-ante prevention measures in the definition of resilience.

ence include the use of inventories or a switch to self-produced inputs (e.g. the use of backup generators in case of electricity disruption) (Rose et al., 2005).

Opportunities like these can be integrated into damage assessment in a variety of ways. For instance, a range of attempts have been made to adjust standard Input-Output Analysis to accommodate features of resilience (Duchin, 2009; Henriet & Hallegatte, 2008; Oliva et al., 2010). A more natural approach is to resort to Computable General Equilibrium (CGE) modeling, where market outcomes are truly micro-founded, i.e. are derived from optimizing behavior at the individual level. However, the increase in flexibility associated with the modeling of preferences also raises the data requirements for parameter calibration.

In addition, parameter specification is complicated by the fact that the degree of input substitutability is highly sensitive to the length of the examined response period. In the very short-run, firms are still dependent on existing contracts, substitutability can thus presumed to be very low. For this scenario, Input-Output Analysis (or alternatively a CGE model with a very low elasticity of input substitution) can yield adequate estimates. For a medium-run analysis, a higher level of substitutability should be presumed, asking for the flexibility of a CGE or similar approach (Rose & Guha, 2004). Concerning the lengths of these distinct recovery phases, no general statements can be made, as they again depend on nature and extent of the analyzed event. Consequently, existing results are highly specific to the chosen settings. A further obstacle in parameter choice is the tendency of people to show different behavioral patterns in crisis situations, e.g. being forced to cope with scarcities could render them more inventive.[8] In this vein, Rose (2004) further distinguishes between inherent and adaptive resilience, the latter reflecting extra-efforts of people to compensate supply chain disruptions. Moreover, the functioning of markets as coordination devices might be generally disturbed due to the vast extent of insecurity and information gaps large-scale disasters bring about. A consequence is that observations made in pre-disaster situations often do not represent valid indicators for actual crisis behavior.

The impact of reconstruction activities

Another factor aside from resilience that can damp output losses in the medium-run is the demand surge associated with reconstruction. Naturally, this mostly favors the sectors construction and transport[9]. By raising income and thus purchasing power of workers, this could turn into a general stimulus for a post-disaster economy. The quantitative impact on total production is however conditional on the current position with-

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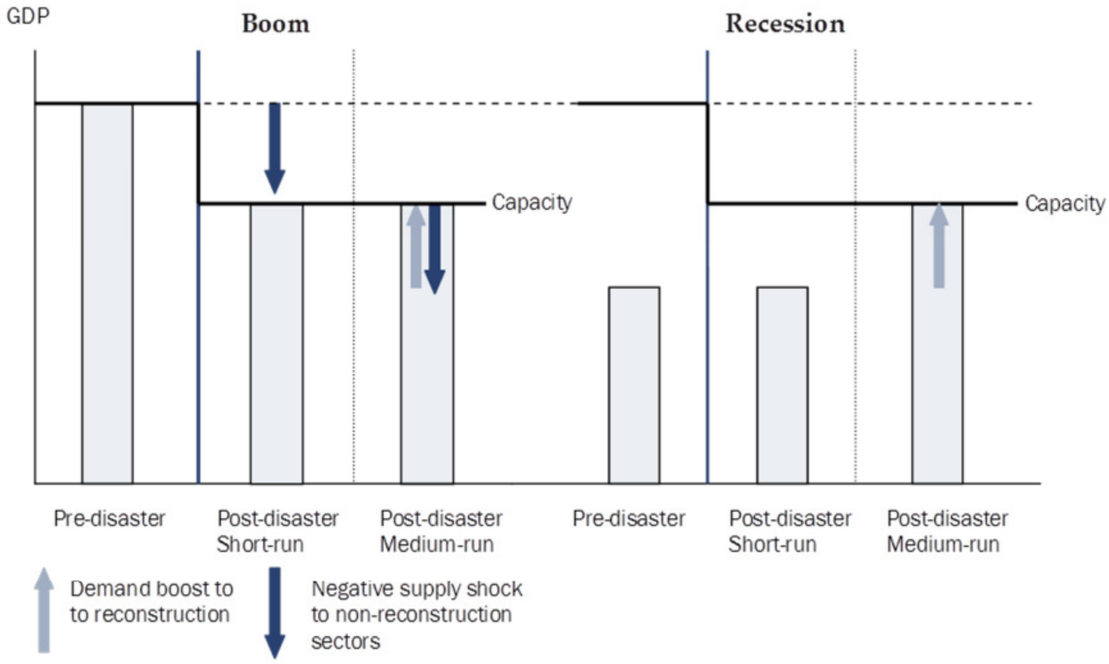
[8] For example, as documented by Rodriguez et al.(2006) for the aftermath of Hurricane Katrina.

[9] See Kirchberger (2012) for evidence on the labor market effects in these sectors.

in the business cycle, as demonstrated by Hallegatte & Ghil (2008). If the disaster hits the economy in a boom phase where productive capacities are almost fully exhausted, there are no idle resources left that reconstruction could draw upon. Hence, there is no opportunity for output to increase in the reconstruction stage. Factors employed in reconstruction are then simply redirected from other activities. This can be different in recession, where capacities are usually underutilized. By making use of these additional capacities, reconstruction could indeed induce output to rise in response to a disaster. Both (idealized) situations are depicted in Figure 1. However, even if production should experience a boost due to reconstruction, this should not be misinterpreted as a positive welfare effect. Reconstruction activity merely represents the restoration of a destroyed share of the society's stock of wealth. Hence, for the purpose of welfare evaluation, reconstruction should be left aside (Rose, 2004).

Figure 1: Stylized output response at different positions in the business cycle



Source: Own representation

To summarize, attempts to consider the impact of catastrophes on market transactions have so far brought a considerable amount of indirect effects to light. Nevertheless, barriers to a quantitative assessment of important aspects have yet prevented the establishment of a reliable net measure summarizing the multitude of these side effects. Since the relevance of supply chain effects is undisputed, enhancing the flexibility of estimation methods in that sense will continue to represent a main strand of future investigations.

2.3 | Indirect long-term effects: impact on investment decision

Even after reconstruction has been completed, a catastrophe can continue to affect market transactions in the economy via its influence on investment spending. This could be triggered both by changes in the current returns to certain assets and by changes in expectations. Whether this can guide the economy to a different growth path is determined by the interplay of technology and factor accumulation.

Competing theories on the question of long-term damage

From a neoclassical point of view, the consequences of a disaster for growth of GDP per capita are expected to be of short-term nature, i.e. should taper off over time. In aggregate terms, the direction of the short-term effect depends on the disaster's instant impact on the capital-to-labor ratio (Loayza et al., 2012). For the following discussion, we restrict our attention to catastrophes where economy-wide damage is limited to the destruction of physical assets, presuming that neither size nor future growth of the working population are affected (i.e. the impact of deaths or outmigration on total labor supply is assumed to be negligible). Hence, the formal interpretation is that of an unexpected depreciation of the economy's stock of physical capital. With shrinking marginal productivity as assumed by the standard Solow framework (Solow, 1956), the immediate impact of such a decline in physical capital is an increase in the marginal productivity of each additional amount of money saved and invested. Despite the destruction taken place, growth rates are thus expected to rise immediately after a disaster hits the economy[10]. This increase, however, is not persistent, but simply serves to compensate the initial negative level effect on production. Growth slows down again such that, in the longer term, the economy approaches again the pre-disaster growth rate. As a result, production converges to its potential level in the absence of the shock, implying that disasters exert no long-run impact on an economy's productive capacities (see graph 2.A).

A key assumption for this to hold is that the technology of capital usage is exogenous, i.e. remains unaffected by the cataclysmic event. This can be questioned with regards to simultaneous side effects. One effect discussed by the literature is the occurrence of a capital upgrade in the course of reconstruction. Private as well as public decision-makers might see a chance to replace destroyed assets by updated capital embodying new technologies (Albala-Bertrand, 1993). In this way, disasters could become physical equivalents to the processes of creative destruction, described as the main driving forces of technological change by Schumpeter (1934). If this takes the form of a

[10] When considering endogenous savings as in the Ramsey-Cass-Koopmans version (Cass, 1965), this catch-up effect is even more pronounced due to an increase of the savings quota.

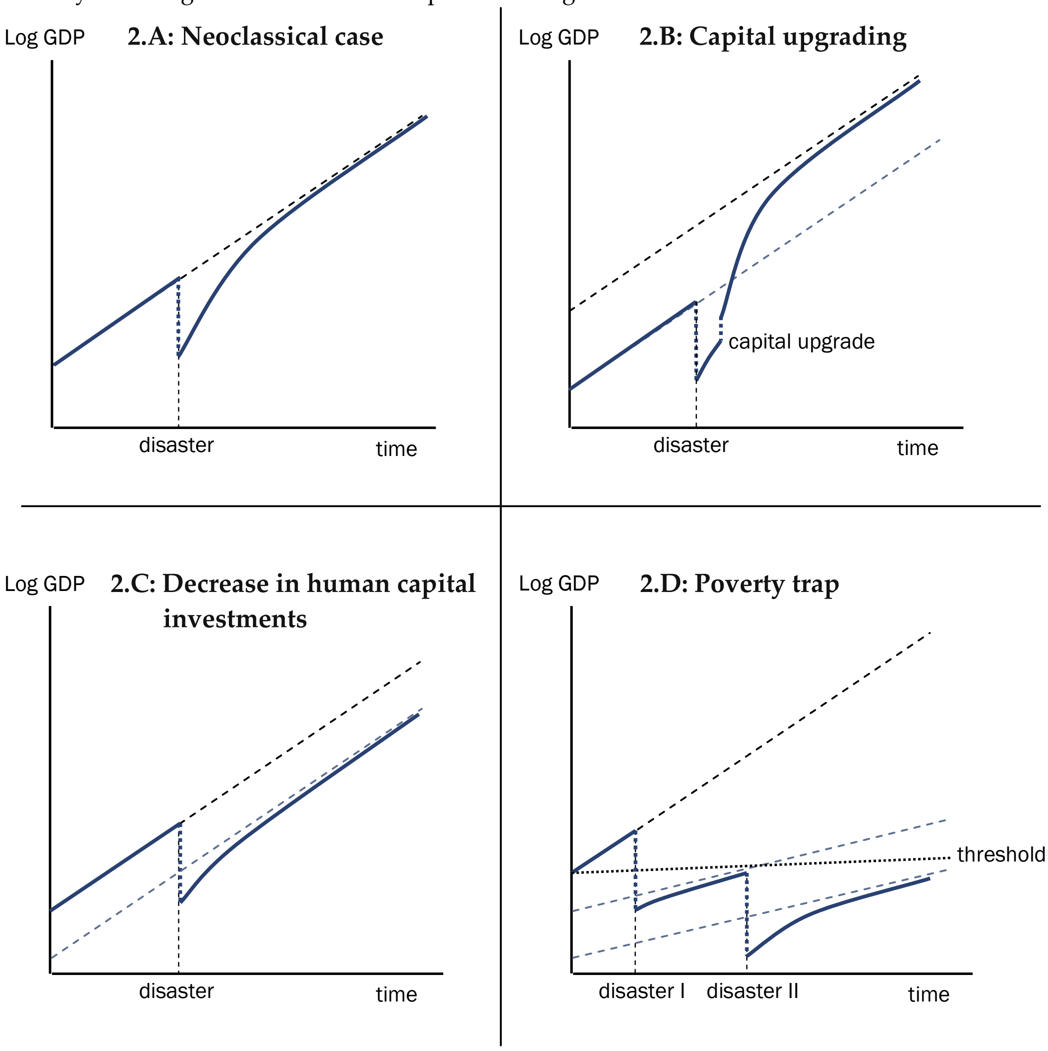
one-off effect, it will not generate persistently higher growth. Nevertheless, it can induce a persistent level effect, raising the productive capacity at any future point in time (see graph 2.B). If disasters are able to stimulate innovative activity, e.g. by emphasizing the need of continuous technology upgrading as a response to disaster risk, they could even exert a positive long-run effect on the growth of GDP.

Additionally, a connection between disasters and long-run growth can arise from side effects on human capital investments. The nature of this side effect is however not obvious. Depending on the type of investment rationale assumed, theoretical reasoning is able to provide arguments for both a positive and a negative impact of catastrophes on educational activities. Under the assumption of a shrinking marginal productivity for all factors, a disaster mainly characterized by the destruction of physical capital lowers the return to human capital investment relative to physical capital. A conclusion would be that people devote less of their savings to finance learning activities and more to investments into physical assets in the aftermath of a disaster. This is amplified when a catastrophe involves the destruction of educational infrastructure. If reconstruction is not undertaken soon enough, the lack of opportunities can cause a permanent setback in human capital formation, potentially guiding the economy to a lower growth path (Lucas, 1988) (see graph 2.C).

Ambiguity in the direction of the effect is introduced by considering the individual trade-off between time spent working and time spent studying. As Baez et al. (2010) note, the opportunity costs of education could both rise and fall in response to a disaster. On the one hand, the necessity to engage in reconstruction activities might leave people less time for studying. On the other hand, if massive destruction leads to a cutback of labor demand and a corresponding decline of wages, perceived opportunity costs of education could also be lowered. However, the presence of an income effect on labor supply implies that even with falling wages the share of time devoted to working might be raised. This is particularly relevant in case of highly imperfect credit markets: In the presence of binding borrowing constraints, shrinking wages force workers to increase their workload in order to smooth consumption over time. This can be especially detrimental in developing countries, where children are expected to contribute to the generation of family income. Parents might be inclined to take their children out of secondary school or at least reduce family expenditures for education (Jacoby & Skoufias, 1997).

The existing evidence overwhelmingly points to a negative relationship between the frequency of catastrophes and human capital formation. For instance, among the most recent investigations, cross-country studies like Cuaresma (2010) and McDermott (2012) discover a significantly negative impact on secondary school enrollment, while Kim (2008) detects a likewise negative effect on the rates of secondary school completion. An exception is Sacerdote (2008), who analyzes the effect of involuntary school switches after Hurricane Katrina. He finds that the performance of evacuees from the lowest performing schools has considerably increased three years after displacement. This further stresses that disasters can have subtle consequences at the individual level, which in turn might also affect the economy's aggregates over a longer time horizon.

Figure 2: Stylized long-term evolution of output according to different theories



Source: Own representation

Finally, a long-run effect on output would also be consistent with the notion of discontinuities in development. According to some theorists like Nelson (1956) and Durlauf (1991), the process of economic development is characterized by a discrete transition between distinct stages. If a threshold in the level of some critical performance measure like output or human capital is exceeded, the economy switches instantly to a superior technology (i.e. it experiences a 'take-off'). Within this framework, the occurrence of a major catastrophe has exactly the opposite effect. It can imply that the economy bounces back to a lower development stage[11]. In this light, Hallegatte et al. (2007) argue that economies frequently hit by disasters can end up caught in a 'poverty trap' with persistently low growth rates. If the period between two disasters is too short for the economy to fully recover, resources desperately needed for technology adoption could be permanently stuck in reconstruction activities. This scenario is depicted in graph 2.D and seems particularly appropriate for some small developing economies.

Empirical evidence on long-run effects

In testing the net effect on long-term growth, a range of very different econometric strategies have been applied by researchers. A basic distinction concerns the composition of the control group in assessing the causal effect of disasters. In approaches where estimates are gained from cross-country Panel models, like Loayza et al. (2012) and Jaramillo (2009), this control group basically consists of all unaffected countries irrespective of whether they share comparable economic characteristics or not. As Cavallo et al. (2010) note, this can bias inference, as estimates might capture deviations in time trends which have nothing to do with the occurrence of the disaster. Alternative approaches therefore explicitly compare the evolution of output in disaster-struck regions with a counterfactual benchmark. This benchmark can consist of time series projections of models fitted to pre-disaster data for the country itself (Berlemann & Vogt, 2007; Hochrainer, 2009) or for a synthetic control country (Cavallo et al., 2011). This diversity of methods results in a similar diversity of outcomes. While Hochrainer (2009) and Raddatz (2009) find evidence for a negative effect of disasters on growth, the results of Jaramillo (2009) and Cavallo et al. (2010) rather suggest neoclassical long-run neutrality. Finally, Skidmore & Toya (2002) and Yasuyuki et al. (2011) even obtain positive long-run effects, which Skidmore & Toya (2002) interpret as some confirmation for the capital upgrading hypothesis.

Obviously, besides the particularities of affected regions, it is also the heterogeneity of catastrophes themselves that impedes the establishment of general propositions through empirics. For instance, studies based on a categorization of disasters generally conclude that only moderate disasters can be beneficial for growth, while severe ones cannot. Moreover, developing economies are suffering from significantly worse effects, especially when they can already look back at a history of similar events (Loayza et al., 2012; Fomby et al., 2009; Jaramillo, 2009). These results point to the relevance of discontinuities like 'poverty traps' in assessing disaster outcomes. Moreover, the analysis of Fomby et al. (2009) demonstrates the distinctiveness of specific types of catastrophes:

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[11] Alternatively, the same mechanism can be explained by discontinuous savings rates through subsistence consumption (see Kraay & Raddatz, (2007)).

while floods have the tendency to exert a positive impact, storms tend to have a negative one. Future approaches will thus have to devote more efforts to differentiation in order to add robust insights to this complex topic.

3 | Coping with catastrophe risk in a decentralized economy

3.1 | Protective measures and pro-active response

In practice, decision-makers face considerable resource limitations in securing the provision of key infrastructure services. Protecting critical infrastructure against a multitude of existing threats involves various types of trade-offs. One has to decide on which type of threat to shield against, which facility to protect the most and which share of worker time to devote to security routines. Essentially, security planning can be viewed as a collection of interrelated problems of constrained optimization. While decisions can be principally based on calculus, a solution algorithm should also account for the behavioral implications. Any measure undertaken can have repercussions on the behavior of other planners as well as potential perpetrators, which in turn influence its effectiveness. In this regard, economic concepts like game theory can sharpen the senses on the strategic nature of infrastructure protection and provide the necessary intuition to deal with real-life threats.

The case of independent sites

This becomes already clear by considering the simplest setup of a security investment problem: the decision how to allocate a fixed budget for protective measures among a range of independent infrastructure sites, each basically exposed to the same threat. The probability that a site turns inoperative due to an attack (i.e. the failure risk) is a decreasing function of the amount of resources spent on its protection. Golany et al. (2009) have investigated optimal allocation rules for this scenario under the reasonable assumption that the defender seeks to minimize expected damage. In particular, they demonstrate how optimal spending differs between the two major types of risks: natural disasters and terrorist attacks. To minimize damage inflicted by a natural disaster, priority has to be given to the protection of those sites where the efficiency of protective measures is the highest (i.e. where the means invested can cause the strongest decline in failure risk).

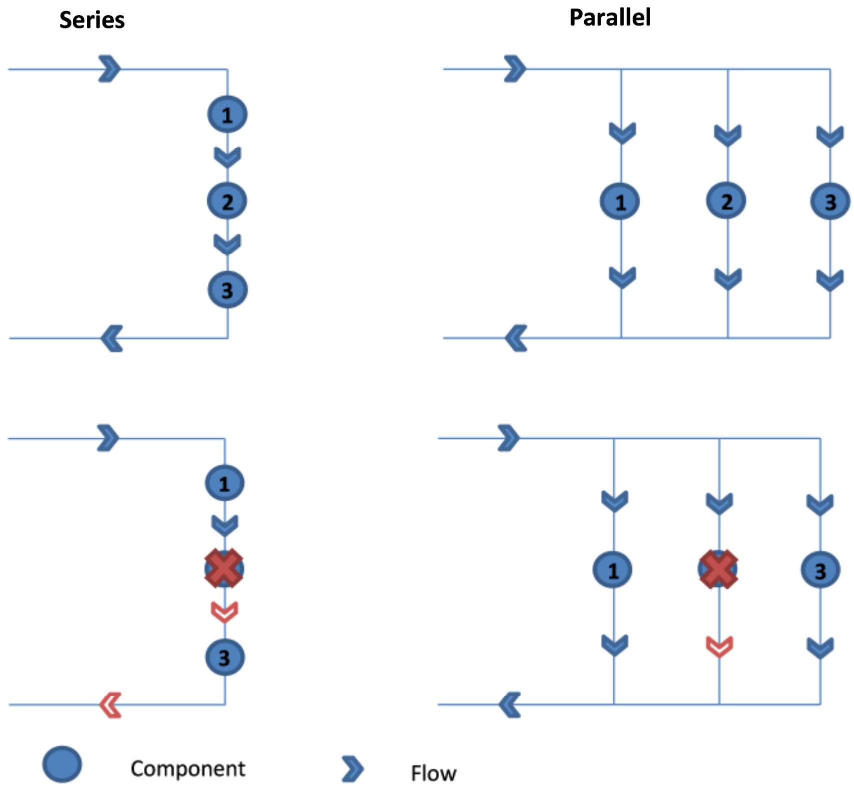
In contrast, when facing a terrorist threat, the most vulnerable sites (i.e. with the highest failure risk) should always be shielded with priority, even if marginal efficiency of the money invested might be higher at other sides. Expected damage is minimized when all sites end up with the same degree of risk exposure. The difference is the strategic response of attackers. Provided that terrorists are not completely unaware of the strength of protection granted to different sites, they will always focus on attacking the site with the highest fatality risk after considering protection. Powell (2009) confirms these results for the scenario of a sequential game, proving that such a minmax-behavior represents a dominant strategy for a defender. Golany et al. (2009) refer to this type of risk as strategic risk, as opposed to the pure probabilistic risk associated with natural disasters. According to Brown et al. (2006), strategic risk in general represents a tougher challenge to the defender, as a rational attacker usually benefits from two prime advantages. First, she can focus on attacking a subset of very vulnerable sites, while the defender bears the responsibility to protect the complete set. Second, information on the resilience of certain targets is often public. At the same time, the defender tends to have only very limited knowledge on resources and strategic objectives of the attacker.

The case of interdependent sites: insights from reliability analysis

While the simple problem of defending independent sites sheds some light on the rationale of safety measures, it offers only limited guidance on the protection of real-world infrastructure. Foremost, any modeling framework should account for the strategic implications of existing interdependencies. Indeed, one distinctive feature of modern infrastructure facilities is their interconnectedness (Macaulay, 2009). Depending on the way components of a system of infrastructure services are nested, the corruption of just one component due to a catastrophic event could have severe consequences for the operability of the total system. This sensitivity to the mode of nesting, in turn, requires the use of engineering methods to determine appropriate security responses. In recent years, reliability analysis as one important interdisciplinary field in safety engineering has increasingly been applied to analyze the optimal degree of protection against external threats (e.g. Levitin, 2002; Bier et al., 2005; Azaiez & Bier, 2007). In these works, the probability of system failure is represented as a technology-dependent function of failure probabilities of the single components. This is typically combined with an optimization approach: failure risk is minimized by allocating resources to the protection of single components.

One fundamental concept in this kind of analysis is the distinction between **series** and **parallel** systems. It indicates in how far the functionality of the aggregate system depends on the functionality of the single components. In a pure **parallel** system, components are perfectly substitutable in the sense that the occurrence of system failure would require that each component gets corrupted. For instance, this can apply to systems where components are designed to carry out very similar tasks. Intuitively, the redundancy implied by this feature is advantageous to a defender. Unlike in the case of independent facilities, the exposure to malicious attacks does not require a strict focus on the weakest components. Hence, measures to shield against both major types of risk can be undertaken in light of efficiency considerations, employing funds where they yield the biggest reduction in component risk.

Figure 3: Series and parallel systems, with component failure (lower graph)



Source: Own representation

In a **series** system, the failure of just one component induces the whole system to collapse, regardless of the performance of other components.[12] This property has crucial consequences for the efficiency of investments in risk-management. Specifically, it implies that the effectiveness of a security upgrade of one component strongly hinges upon the reliability of other components. In the extreme case where one out of many components could never stand any disastrous event, investments in other components would be completely useless. Since marginal investment efficiency increases with re-

[12] In cases where failure risk at component level is distributed independently, the probability that a system does not fail (i.e. that it succeeds) within a certain time span is thus simply calculated as the product of success rates of the single components.

duced vulnerability of other components, equalizing marginal efficiencies represents an optimal rule for tackling probabilistic risk.[13]

However, unlike for **parallel** systems, this rule cannot be applied to strategic risk. A terrorist group seeking to maximize the probability of system failure by launching an attack on one of its components will always choose the most vulnerable one as their target. Hence, marginal cost efficiency is not a relevant criterion in protecting a series system against a terrorist threat. Even if investment in the stability of less vulnerable components might yield a stronger decline in component risk, it cannot improve the reliability of the aggregate system. An appropriate allocation rule is thus to shield the most vulnerable components with priority until their exposure equals the exposure of the second most vulnerable, after which an equal amount is invested into both components and so forth (Bier et al., 2005). If sufficient resources are available for risk mitigation, the optimum is characterized by a situation in which expected failure risk is equalized between all components.

Hausken (2008) notes that **series** and **parallel** systems also differ substantially in the strategic position of the defender: In a pure **parallel** system, the defender benefits from the substitutability of components. In a pure **series** system, it is instead the attacker that benefits from a substitution effect: the opportunity to disable the system by attacking principally any of its single components allows her to focus her efforts on the weakest component.

Complexity is added when considering alternative objective functions for the attacker (e.g. maximizing the probability of inflicting a certain level of damage on a system (Holmgren et al., 2007)) or introducing alternative defense tactics for the defender (such as deploying false targets (Hausken & Levitin, 2009). Besides, a considerable body of Operational Research literature extends the simplified dichotomy of **parallel** and **serial** systems to the more realistic case of multi-state systems consisting of **series** and **parallel** subsystems. (e.g. Levitin, 2007; Azaiez & Bier, 2007). In these setups, the defender is not only asked to decide on the optimal level of protection for the single components, but also on their optimal degree of separation. Here, separation means the extent to which the system is split into independently functioning parallel subsystems. As a consequence, results become highly sensitive to the specific type of system considered, preventing any general propositions on optimal strategies. What remains to hold is that a higher degree of redundancy in the functionality of different components (i.e. a structure more strongly based on parallel components) implies a higher overall reliability due to higher flexibility offered to the defender (Bier, 2005).

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[13] The exact distribution of resources resulting from an application of this rule is technology dependent.

Barriers to efficient protection

While these optimization-based setups are able to incorporate a considerable degree of real-life complexity in terms of technical network features, their application to critical infrastructure protection suffers from important shortcomings in other respects. With regards to strategic risk, one shortcoming concerns the need to presume a reasonable objective function for the attackers. If their ultimate goal is to disable the system, expected physical damage can serve as such. Nevertheless, terrorist preferences can be characterized by a diverse set of goals. In this, physical destruction might only serve as a means to fulfill superior psychological aims like the inducement of fear, the gain of political influence or the promotion of group awareness (Crenshaw, 1981; Ganor, 2005). In general, it is not evident that inflicting the highest possible level of damage will always be compatible with these goals. In the end, optimization rules should be adjusted to the specific circumstances.

The second barrier to a direct application is the concept of a central planner allocating resources to risk mitigation. In modern Western economies, transmission networks of key infrastructure services such as utilities and communication tend to be operated by private companies instead of public authorities. Distinct segments are potentially run by companies with distinct owners. In this case, the problem how to guarantee an optimal level of protection cannot simply be solved by means of aggregate optimization. The reason is that such an approach ignores the interdependency of investments into security undertaken by operators of different components. Precisely, it does not consider that an improvement in the system's reliability resulting from a security upgrade of one component represents a positive externality from the perspective of owners of the other components. In other words, system security exhibits the features of a public good in the eyes of network operators, giving rise to strategic decision-making in risk mitigation (Kunreuther & Heal, 2003).

Total provision of public goods is normally given by the sum of amounts produced by all the members of a society or network. However, this does not necessarily apply to the maintenance of security in a network structure. Returning to the fundamental distinction between **series** and **parallel** systems, it is only true for **parallel** systems that security investments by each operator can make the same contribution to the reliability of the system. With regards to series systems, protection can instead be characterized as a special case of a public good, which is referred to as a weakest-link public good by Hirshleifer (1983). Since reliability here strongly or even exclusively (in case of malicious attacks) depends on the failure risk of the weakest component, its level is essentially determined by the security efforts undertaken by the owner of this component. An important implication is that operators in general will only invest a socially efficient amount into protection if they expect all other operators to do so as well. Hence, individual optimization is subject to a considerable degree of strategic interaction. In the absence of a coordination mechanism, basic economic theory suggests that this could trigger an equilibrium characterized by underinvestment compared to the social optimum.

Kunreuther & Heal (2003) have investigated possible outcomes of a comparable game. They use the illustrative example of airline companies choosing whether to invest in a baggage screening system. Interaction stems here from the fact that in the course of transfer flights baggage screened by other companies will have to be transported. It might be that one bag contains a bomb which has been undetected due to insufficient precautions taken by the company on whose airplane the bag has first been loaded. This imposes the external threat of an explosion on the airplanes of other companies the bag is transferred to. The authors show that depending on damage probability and cost structure the game can exhibit multiple Nash-equilibra. Among these is also a prisoner's dilemma, i.e. a situation in which neither company is willing to invest even though baggage screening would be in the best interest of each single company.

Bier & Gupta (2005) have extended this scenario to a dynamic context of time-dependent protection. This is done to account for the fact that protection might only be successful in postponing a coordinated attack, not in eventually preventing it. In this way, they shed light on the role of time preferences: only decision-makers with sufficiently high time discount rates are willing to invest in security, as the benefits from postponement are otherwise considered to be too low. If decentralized security provision within networks fails, this could hence in part also be explained by heterogeneity regarding time preferences.

Moreover, problems of underinvestment potentially not only arise from a lack of internal network coordination, but might be fueled by hopes of network operators for a public bail-out in the event of serious disaster damage. Such an expectation can be rational from an individual point of view: in representative democracies, policy-makers are largely unable to make credible commitments not to provide relief in the aftermath of a disaster. The reason is that voters have a tendency to punish governmental inactivity in the course of large-scale disasters, as empirically confirmed by the works of Healy & Malhorta (2009) and Gasper & Reeves (2011). This is the essence of the so-called **Samaritan's dilemma** (Moss, 2002). It can induce policy-makers to devote more resources to post-disaster spending than to preventive measures, which can further aggravate the problem of underinvestment as companies will expect public funding in the case of a catastrophe.

The pro-active response dilemma

Finally, similar coordination failure can also occur with regards to pro-active responses to threats in an international context[14]. Following Arce & Sandler (2005), we define a pro-active policy as any direct action taken against a terrorist or criminal group and their supporters. If one country weighs the costs and benefits of taking isolated steps to weaken an internationally operating attacker, it basically faces the same asymmetric pay-off as in case of passive network protection. The costs of such a strike are borne by the country itself, while the benefit of eliminating a potential threat is reaped by all countries at risk. The public good nature of pro-active policies can thus result in insufficient engagement by all countries, which eventually favors global terrorism[15] (Sandler, 2003). In a dynamic perspective, this problem is aggravated as any active response can provoke retaliation measures by the terrorists that further increase the costs of engagement (Sandler & Enders, 2004).

This basic dilemma underlies principally any kind of measure directed at supranational terrorism. The consequences of coordination failure among a group of target countries are however likely to differ. Again, they depend on how the effectiveness of a measure hinges upon the contributions of the group members. Some responses such as the freezing of financial assets of a terrorist group or denying shelter to their leading activists are only effective if all group members participate, i.e. agree to bear the private costs of engagement (Arce & Sandler, 2005). If just one country refuses to participate, it could become a safe haven from the perspective of terrorists, ruining any efforts undertaken by other countries. Obviously, this weakest-link feature is especially fatal when the risk of being attacked is distributed very asymmetrically between countries, giving the least affected countries low incentives to engage. In these situations, there will be pressure to enter into negotiations on a coordinated attempt, most likely under the leadership of the country with the largest exposure.

This is different for measures like the gathering of intelligence. Knowledge gained on terrorist activity, if shared among the target countries, represents a public good whose level of provision is determined by the aggregated contributions of all countries. In principle, a sufficient level could be achieved even with some of them not contributing at all. According to Arce & Sandler (2005), an asymmetric exposure to the terrorist danger can potentially mitigate the consequences of free rider behavior. Leaders of the most vulnerable country might be prepared to invest in countermeasures even if

[14] In line with large parts of the game theory literature we focus here on manmade threats, as tackling potential sources of natural disasters like climate change involves a very long-term engagement with not yet well-understood effects.

[15] Sandler & Siqueira (2007) demonstrate that this result is maintained when considering decision-making in a representative democracy. Voters are inclined to elect policy-makers that curb pro-active policies in order to free-ride on the countermeasures of other country, resulting in a Nash-Equilibrium with insufficient activity.

others do not follow, as a comparatively large amount of the benefits can be internalized. Hence, while underinvestment represents a likely result in the absence of appropriate regulation, its seriousness is highly sensitive to both the type of network structure and the range of measures considered.

The tendency to underinvest in physical protection increases the significance of insurance and other financial hedging instruments for coping with disaster risk. It turns out that the particularities of catastrophes also impair the ability of financial markets to provide sufficient hedging.

3.2 | Insurance and alternative financial hedging instruments

If aggregate uncertainty in an economy is characterized by a large pool of purely individual (i.e. uncorrelated) risks, insurance can represent an efficient way of eliminating this risk through diversification. By increasing the number of independent policies issued, an insurance company can always reduce the total variance of its portfolio. As a consequence, provided that insurance markets are sufficiently competitive, the elimination of any aggregate market risk allows insurers to set premium rates at actuarially fair levels (i.e. at levels which equal expected damage within a period).

Unfortunately, such an ideal world does not allow for the occurrence of disastrous events. Since these imply a large number of policyholders to be simultaneously affected, the resulting correlation of claims prevents insurers from creating perfect hedges. More precisely, catastrophe risk can be considered a composite of individual and collective risk elements (Kobayashi & Yokomatsu, 2000): while damage is generally spread among a large group of people, the extent of individual losses varies.

Nevertheless, Borch (1962) has demonstrated that collective risk can be effectively dealt with within the scenario of a reinsurance market where claims are perfectly tradable between insurance companies[16]. A pareto-efficient allocation of aggregate risk is here characterized by a situation in which all insurers hold an ex-ante identical liability portfolio, leaving no room for further diversification by means of exchanging claims. This result mimics the more general proposition for optimal asset holdings under risk aversion known as the Capital Asset Pricing Model (CAPM) (Sharpe, 1964): the composition of individual portfolios should be identical and thus equal the composition of the market portfolio. The variance of this aggregate bundle of claims then basically represents the collective part of catastrophe risk.

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[16] e.g. by emitting Arrow securities offering payouts only in the absence of insurance claims (Arrow, 1964)

Sources of market failure I: misguided incentives

In practice, however, insurance companies face several limitations in applying this concept to these types of large-scale risks. First of all, it can be reasonably argued that the well-known problems resulting from information asymmetry in the relationship between insurers and policyholders are even more pronounced in the case of catastrophe insurance. On the one hand, the consequences of moral hazard effects after contracts have been signed (Ehrlich & Becker, 1972) could be extraordinary devastating. As discussed in the previous section, the tendency to free ride in protection can seriously raise the vulnerability of an integrated system towards major risks. If fair insurance is available, decision-makers not only have an incentive to neglect the external damage resulting from sudden component failure, but the damage occurred at their own component as well. This further reduces the willingness to invest in security upgrades. This false incentive tends to become more relevant with both increasing scale of potential damage and decreasing frequency, as expected insurance payments are then likely to exceed the transaction costs of making the claim (Ehrlich & Becker, 1972).

On the other hand, consequences of the issue of adverse selection can also be more fatal. Unless insurers are able to identify persons being more vulnerable towards catastrophic events and charge them with higher premiums, the resulting premium structure would induce low-risk individuals to remain uninsured against disastrous events. Existing insurance portfolios would thus basically consist of a small pool of strongly correlated high-risk policies (Pauly, 1974). Both types of market imperfections are able to trigger situations in which the market either does not offer sufficient coverage of disaster risk or only at rates perceived as excessive by members of high-risk groups, thereby evoking an underinsurance problem.

Sources of market failure II: inherent uncertainty

However, underinsurance with regards to large-scale risk is also due to other factors more specific to disaster insurance. These are, according to Jaffee & Russell (1997), more suitable for explaining potential market failure. In particular, it is the character of disasters as low probability-high consequence events which complicates the assessment of expected losses from the perspective of both buyers and sellers of catastrophe insurance (Kunreuther & Pauly, 2009). The fact that these events are very rare implies a lack of sufficient experience concerning frequency and magnitude of damage.[17] Consequently, insurance companies face high information costs in determining appropriate risk premiums. A common way to account for the resulting uncertainty is to add ex-

[17] Comparing the two major risk types, this is even truer for terrorist attacks than for natural disasters. The specificity of each terrorist threat often implies a total lack of relevant experience, while concerning most types of natural disasters at least some historical data can be consulted (Kunreuther & Pauly, 2009).

plicit "ambiguity loads" to premiums acting as risk buffers (Skees et al., 2007). Nevertheless, this does not prevent miscalculations, which is documented by the strong fluctuations in premium levels observed in the aftermath of actual mega losses.[18] For the same reason, residents of disaster-prone areas may put too little effort into reducing their exposure through insurance, as they are unaware of its real extent.

Alternative explanations for the same behavior can be given based on psychological considerations: even if information on damage probabilities is easily available, people might tend to underinsure as a consequence of bounded rationality. Experimental evidence shows that people often fail to distinguish between low- and zero-probability events in decision-making, as expressed by a ''this can't happen to me" attitude (Kunreuther et al., 2001). Another type of irrationality discussed is the possible existence of a probability threshold below which individuals see no reason to deal with the consequences of an event at all (Kunreuther, 1996). The empirical evidence on whether observed low insurance rates can really be attributed to these factors is however mixed. While studies like Slovic et al. (1977) and Ganderton et al. (2000) detect a positive correlation between loss probability and the rate of insurance purchase for constant values of expected loss, a more recent laboratory study undertaken by Laury et al. (2009) finds no signs of such a relation.

Sources of market failure III: bankruptcy risk

Apart from informational concerns on supply and demand side, a serious obstacle to the provision of disaster insurance is the prevailing imperfection of capital markets, especially with regards to the existence of bankruptcy costs. The necessity to avoid default forces insurers to consider survival constraints in portfolio planning, i.e. existing funds must be able to cover claims in worst-case scenarios irrespective of actual damage probabilities (Stone, 1973). With respect to catastrophes, period revenues from fair insurance premiums are usually insufficient to finance the claims resulting from mega losses, creating the same outcome of insufficient provision and/or excessively high premiums (Jaffee & Russell, 1997). The financial stress imposed by unpredicted cataclysmic events on insurance companies could at least in the short-run be exacerbated through the response of stock markets: A downfall in the prices of shares (e.g. reflecting the uncertainty whether insurers are able to cover all losses) would further raise the debt-to-equity ratio of affected companies, thus raising their future refinancing costs (Michel-Kerjan & Morlaye, 2008)[19].

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[18] For instance, reinsurance premiums in the United States experienced a tremendous increase of 76 percent after Hurricane Season 2005(Carpenter, 1997).

[19] In the past, the actual evolution of insurance companies' stock prices in the aftermath of catastrophes has shown a mixed pattern. For instance, Gangopadhyay et al. (2012) identify a clearly negative response resulting from Hurricane Kathrina, while effects of Hurricane Rita (both 2005) are revealed to be more mixed. This is attributed to the presence of a countervailing positive impact on insurance de-

However, in contrast to behavioral issues, the problem of financial bottlenecks arising from catastrophes can in principle be mitigated by complementary reinsurance. In this regard, the most conventional measure is formal reinsurance, i.e. the decision to enter into a risk transfer contract with a reinsurance company. Given the portfolio size and the global orientation of the leading reinsurers, this guarantees an improved pooling of large-scale risks. The downside is that the required customization of contracts involves high transaction costs. Furthermore, risk-sharing is only transferred to another level and the relationship between insurers and reinsurers is likewise characterized by the issues of information asymmetry mentioned above (Hofman & Brukoff, 2006). Moreover, reinsurance prices could be driven up by the fact that the market is characterized by a fairly small number of suppliers, giving each of them the opportunity to exercise market power in premium setting (Froot, 2001).

CAT-Bonds as alternative risk sharing instruments

Based on these shortcomings, efforts were made to transfer risk to a larger group of anonymous investors through securitization. By splitting up an event-specific risk into a number of tradable assets, insurers gain the opportunity to tap into the immense capacities of capital markets. Specifically, Catastrophe bonds (or CAT bonds) emerged as a first marketable risk transfer instrument in the mid90s, fueled by the devastation caused by Hurricane Andrew and the Northridge earthquake in North America. Over the years, various specifications were offered, primarily differing in the way losses are shared among market participants and in the corresponding trigger event. The first type of indemnity-based CAT bonds was designed such that investors adopt the role of reinsurance companies: in periods where the specified disastrous event does not occur, the buyer receives a fixed interest payment on its principal, financed out of the premium revenues of the seller. If the securitized disaster takes place, the buyer loses his claim on interest payments and also some share of the principal. This share depends on the extent of losses incurred by the seller due to this event. Given the direct linkage to existing portfolio risk, this construction provides insurers with a high degree of hedging against insurance claims (Skees et al., 2007). Hence, this type of capital market instrument most closely resembles direct reinsurance.

However, as the exposure of buyers is closely tied to the exposure of the seller, investors will have a high demand for transparency with regards to the capital structure and investment policy of the insurance company. In essence, the monitoring problems associated with direct insurance are thus not overcome by this arrangement, which

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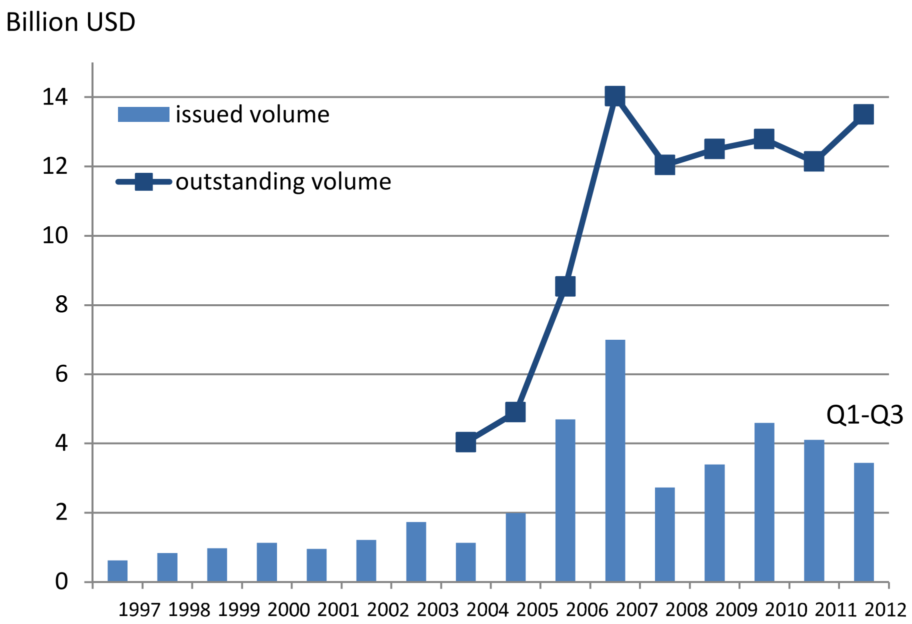
mand by the authors. Similarly, concerning the situation of American insurers after the attacks on 9/11, Doherty et al. (2002) note that the shares of some companies recovered quickly. This is interpreted as a reward for transparency in revealing the extent of losses.

results in additional transaction costs and the expectation of higher returns on the part of investors (Hofman & Brukoff, 2006).

For this reason, index-based and loss-triggered CAT bonds were developed as alternative instruments. They share the feature that investors do not directly compensate the losses of the issuer in the event of a catastrophe. Instead, a fixed amount of the principal is forfeited provided that one or more measures (which are unaffected by activities of the issuer) reach certain thresholds. In case of index-based bonds, the underlying trigger variable is an objective measure, typically a physical parameter (e.g. weather derivatives). Loss-triggered bonds are instead based on average losses of the whole insurance industry within a certain region (Skees et al., 2007). Due to the transparency of the triggering event and its independence from the insurer's investment policy, these products are detached from the moral hazard issues of alternative reinsurance schemes. In particular, they do not give insurers an incentive to increase the overall leverage of their portfolio or to avoid alternative risk mitigation activities. This entails a risk reduction for investors, allowing them to be satisfied with lower average returns compared to indemnity-triggered bonds. Moreover, transaction costs are much lower, as a consequence of higher transparency in the triggering mechanism and in the amount of the related wealth transfer (Hofman & Brukoff, 2006). At the same time, however, the independence of payouts from actual losses implies that these types of CAT bonds only offer an imperfect hedge against insurance claims. Depending on the strength of the correlation of the trigger with the insurance companies' losses, some amount of basis risk remains (Cummins, 2006).

In the years between their first appearance and the recent financial crisis, trading volumes of CAT bonds in general have shown a clear upward trend. The value of newly issued CAT bonds during a year has increased from about 1.12 billion USD in the year 2000 to 7billion USD in 2007 (Kunreuther & Pauly, 2009). Recently, this market segment has recovered quickly from the crisis, with the first quarter of 2012 marking a record with a volume of 1.34 billion USD additional capital being placed on the market (Guy Carpenter, 2012). Moreover, despite events as the Japanese earthquake, the number of investors engaging on the market has increased considerably, with the share of major traditional investors like pension funds increasing from 5% to 20% in 2010 (Munich RE, 2011). This indicates that securitization of large-scale risks as an alternative risk management tool might play an even bigger role in the future.

Figure 4: Evolution of trade volumes of CAT Bonds



Source: Guy Carpenter (www.gccapitalideas.com)

4 | Policies to promote private security investments

The previous analysis has presented reasons why in an environment of unregulated markets private decision-makers tend to underinvest in measures to protect against disasters. Undoubtedly, the occurrence of a major catastrophe would thus raise massive claims for governmental help on the part of people affected, implying that a considerable amount of public budget will have to be spent for recovery aid. While it is surely appropriate to ease the hardship of the most badly affected, this does not constitute an efficient policy to shield the economy against the impact of catastrophes.

Issues with post-disaster aid

First, there is the allocation problem, requiring that decision-makers know which households and firms could make the most productive use of recovery payments. In practice, a lack of information in this regard will lead to allocation procedures that are instead primarily based on the neediness of applicants. Hence, some part of the help offered will represent cross-subsidies to low-productive firms. For instance, this is consistent with the results of Dahlhamer & Tierney, (1998) and Webb et al. (2000) for the recovery of local businesses after Hurricane Andrew and the Northridge earthquake.

They find that businesses which had received public disaster aid were some time latter worse-off than affected businesses which had not, suggesting that efficiency was not the prime criterion in aid allocation. Second, as discussed above, focusing on post-disaster aid further suffocates private preparedness measures by raising expectations of a bail-out (Moss, 2002). Third, insufficient monitoring opportunities regarding the use of assistance can trigger additional moral hazard problems, such as the misuse of aid for consumption instead of investment.

A foresighted policy should thus set its focus on tackling the basic source of under-investment: the positive externality stemming from improved protection. This is best to be achieved by addressing the self-interest of private decision-makers. Conceptually, this task is very similar to the objective of fostering private investments into the abatement of environmental pollution. Hence, the set of policy instruments available is similar as well. A central challenge consists of finding the right mixture of command-and-control-based and market-based approaches.

Fostering private security investments

Command-and-control measures comprise all attempts of direct regulation by defining and enforcing minimum requirements in protection, such as building codes and standards in labor organization and contingency planning (Orszag, 2003). They provide public authorities with immediate control over the nature and extent of protective measures. However, public planners are confronted with high informational needs in choosing the appropriate level of safety, calling for a high amount of resources to be devoted to planning (Jaffe et al., 2003). In addition, the necessary monitoring activity is labour-intensive. As a consequence, regulatory standards are typically associated with higher enforcement costs than market-based instruments.

An alternative (or supplementary) command-and-control approach is the utilization of liability law to internalize existing externalities. Firms that under-invest in protective measures are held liable for the part of disaster-induced losses of other companies attributable to this underinvestment. While this would free regulators from defining ex-ante standards, it similarly imposes a high level of transaction costs on law enforcement. In order to realize claims, the exact cause of a loss needs to be established unequivocally. In case of a widespread damage, this can be extremely difficult, especially concerning interconnected components of infrastructure (Kunreuther & Heal, 2003).

Financial incentives, on the other hand, guarantee more flexibility. These can either take the form of direct payments to firms and households conditional on security-enhancing investments or of indirect benefits like tax credits. Subsidizing private investments into a reduction of vulnerabilities leaves private entities the choice on the optimal degree of safety. In this way, sudden changes in the extent of exposure to certain threats (e.g. a grown risk of terrorist attacks due to military operations) do not necessarily require instant regulatory adjustments. While this generally lowers enforcement costs, additional monitoring efforts will have to be made with respect to the usage of the means provided. There is a danger that subsidies could induce private decision-makers to become less selective in choosing between alternative investment projects, given that a lower amount of own resources is at stake. In turn, this might lead them to undertake investments which are inefficient from a societal point of view. Besides, rent-seeking behavior on the part of firms could imply that some of the investments promoted would have been undertaken anyway, thus representing no more than a replacement of private by public financing (Orszag, 2003). Hence, in relying on market-based instruments, policy-makers need to weight the benefit of higher flexibility against the drawback of leaving more room for moral hazard-type behavior.

Raising insurance coverage

Within the literature, there is a clear consensus that an optimal policy mix cannot solely consist of measures to foster physical protection. Instead, it needs to incorporate feasible solutions to catastrophe insurance as well. Even with highly efficient protection, large-scale disasters can afflict critical damage to various sites simultaneously. Establishing an efficient risk sharing mechanism is thus another major task for regulators. It is complicated by the fact that information shortages on both supply- and demand-side of catastrophe insurance require a solution that affects incentives of both sides on the market. In this regard, policy instruments can again be broadly classified into command-and control and market-based instruments. Concerning the first category, a demand-side measure would be the introduction of mandatory insurance for all firms and individuals, or at least for those which are located in disaster-prone areas. This is the path chosen by French law, where a compulsory insurance against disasters is imposed on all owners of property (van den Bergh & Faure, 2006). Such a step is useful to eliminate the problem of an adverse selection of policyholders and helps to diversify risk by increasing the size of the insurance pool. However, it does not give an answer to the problem of moral hazard-driven behavior resulting from insurance coverage. Hence, this measure in isolation might not sufficiently raise the willingness of insurers to provide disaster insurance.

If inadequate coverage of disaster risk is primarily a result of excessively high premiums, an alternative (or complementary) supply-side measure would be premium regulation, i.e. defining maximum levels for premiums by law or letting public agencies decide on premium levels. In principle, this could represent an option to avoid that customers are forced to pay for the bulk of disaster-related uncertainty via loaded premiums. However, a prerequisite is that regulators have information about which premium level can actually be considered fair under the given circumstances.

In comparison, a policy based on financial support offers more options to improve matching on the market for catastrophe insurance. It can act as a stimulus for both sides of the market. From the perspective of policyholders, this can be achieved by subsidizing the conclusion of an insurance contract. From the perspective of insurers, incentives to supply catastrophe coverage could be increased by the offer to take over a predefined share of losses resulting from catastrophes. In this way, public authorities would operate as alternative reinsurers, thereby helping to compensate market failure in reinsurance[20] While these measures can be useful to overcome incentive barriers, they do not eliminate inherent uncertainty, but simply pass the risk on to the public budget and thus to taxpayers. Even more so, aggregate risk could be enhanced due to reduced incentives for damage mitigation (Jaffee & Russell, 2005).

5 | Conclusion

This study has provided a basic summary of recent work on the economics of catastrophes. It was illustrated that, by applying a range of standard economic tools to disaster research, economists were able to identify several channels through which disasters can exert both short- and long-run impacts on production. Researchers consent that these impacts are not solely driven by a decline of short-run capacities due to physical destruction. Instead, additional effects arise from adaptive behavior of the people affected. Nevertheless, as different behavioral assumptions lead to different propositions, there exist a number of controversies regarding relevance and persistence of particular effects. As demonstrated, empirical analysis has yet been unable to settle most of these disputes. Hence, the collection of more refined data as well as further progress in the development of measurement tools will be essential to deepen our understanding of the intricate relationship between cataclysmic events and human decision-making.

Concerning research on strategies to protect against these events, the ongoing fusion of economic game-theory tools and engineer-based reliability analysis was highlighted. The results of this growing literature teach us that the appropriateness of a strategy is highly sensitive to the degree of system interdependence as well as to the type of threat considered. Despite this complexity, we have shown that optimality rules can still be traced back to basic economic intuition, pointing to the usefulness of economic analysis in devising security concepts. However, a general incentive barrier to a real-life application of these concepts is the non-excludability from the benefits of safety improve-

[20] A prominent example for such a strategy is the Terrorism Risk Insurance Act (TRIA) passed in the US in 2002.

ments. Incentive failure is also relevant in the context of insurance solutions, mainly due to the uncertainty associated with disastrous events. Hence, governmental regulation should both address the problems of insufficient physical protection and underinsurance. For this reason, there is a consensus within the literature that policy recommendations should not be limited to isolated measures. An optimal policy response instead consists of a tailor-made mix of incentive-based and regulatory approaches.

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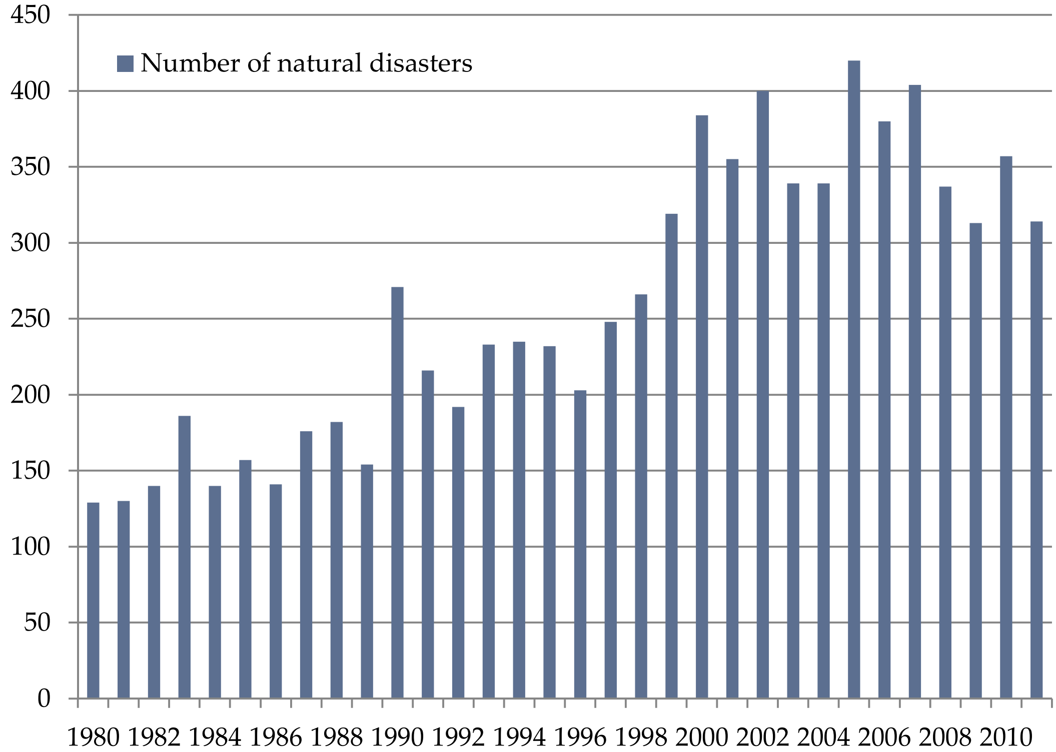
7 | Appendix

FigureA1: Worldwide Frequency of natural disasters within a year



Source: "EM-DAT: The OFDA/CRED International Disaster Database (www.emdat.be)

Table A1: Estimated insurance damage for a range of recent catastrophes

Date	Region	Type of event	Estimated insurance damage (Mio. USD)
1.8.-15.11.2011	Thailand:	Flood	10.000
11.3.2011	Japan	Earthquake, Tsunami	35.000-40.000
22.2.2011	New Zealand	Earthquake	13.000
6.9.-14.9.2008	USA, Caribbean Islands	Hurricane Ike	18.500
19.10.-24.10.2005	USA, Bahamas, Cuba, Haiti, Jamaica, Mexico	Hurricane Wilma	12.500
20.-24.9.2005	USA: LA, Lake Charles, Holly Beach, Cameron, New Orleans; MS; TX, Houston	Hurricane Rita, Flood	12.100
25.-30.8.2005	USA: LA, New Orleans, Slidell; MS, Biloxi, Pas-cagoula, Waveland, Gulfport	Hurricane Katrina, Flood	62.200
7.9.-21.9.2004	USA, Caribbean Islands, Venezuela, Columbia, Mexico	Hurricane Ivan	13.800
17.1.1994	USA: CA, Northridge, Los Angeles, San Fernando Valley, Ventura, Orange	Earthquake	15.300
23.8.-27.8.1992	USA: FL, Homestead; LA; Bahamas	Hurricane Andrew	17.000

Source: Munich RE NatCatService (www.munichre.com)

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