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These doctoral years have been a real roller coaster ride. I was lucky enough to work with passionate professionals and colleagues who shared their knowledge and expertise and helped me to grow both as a person and a researcher. And for this they will always have my gratitude.

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To Francesco and his unconditional love.

Contents

List of Figures

List of Tables

Acknowledgements

Chapter 2 is the reproduction of the paper *"A Review of Public-Private Partnership for the Management of Natural Disasters"*. The full text of the article is also available from the arXiv repository, preprint number 2006.05845.

Chapter 3, **4** and **5** are the reproduction of the paper *"A Public-Private Insurance Model for Natural Risk Management: an Application to Seismic and Flood Risks on Residential Buildings in Italy"* co-authored with Giorgio Stefano Gnecco and Fabio Pammolli. The full text of the article is also available from the arXiv repository, preprint number 2006.05840.

Chapter 6 cites two works in progress:[1]

1. *"Multilevel Spatial Modeling for Risk-Based Earthquake Insurance Premiums in New Zealand"* co-authored with Francesca Marta Lilja Di Lascio and Ilan Noy.
2. *"A Financial Vulnerability Index to Natural Risks for Italian Municipalities"* co-authored with Giovanni Bonaccorsi and Fabio Pammolli.

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[1] Titles are provisional.

Vita

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Abstract

Natural disasters can compromise the economy, solidity, and social well-being of entire nations. To cope with natural risks, some countries have established public-private partnerships with the insurance industry, with generally satisfactorily outcomes. The aim of this thesis is to investigate the role of these partnerships. Chapter 2 reviews the international experience and investigates the main weaknesses of the public-private insurance systems currently in force, that can be traced back to poor risk understanding and inadequate governance. Including risk management into development plans can help ensuring effectiveness of risk reduction, while a more inclusive approach can achieve a better risk understanding. The following three chapters are devoted to the Italian case study and define a public-private insurance scheme for earthquakes and floods. As a first step, Chapter 3 estimates expected losses per individual and municipality through risk-modeling. Chapter 4 defines the insurance model, that departs from the existing literature by describing a public-private insurance intended to relieve the financial burden that natural events place on governments, while at the same time assisting individuals and protecting the insurance business. Though earthquakes generate expected losses that are almost six times greater than floods, we found that the amount of public funds needed to manage the two perils is almost the same. Lastly, Chapter 5 tests whether jointly managing the two perils can counteract the negative impact of spatial correlation. Some benefit from risk diversification emerged, though the probability of the government having to inject further capital is still considerable.

Chapter 1

Introduction

Natural risks pose a broad range of social, financial, and economic issues, with potentially long-lasting effects. Historically, governments have mostly addressed the financial effects of natural events on an ad-hoc basis, but countries are now increasingly focusing on proactive planning before a disaster strikes (World Bank, 2014). Among others, OECD, G20 (OECD, 2012), the World Bank and GFDRR (World Bank, 2014) claim that governments should guide citizens towards recovery by implementing both risk reduction and financial protection. In particular, the World Bank (2014) argues that *"financial protection complements risk reduction by helping a government address residual risk, which is either not feasible or not cost effective to mitigate. Absent a sustainable risk financing strategy, [...], a country with an otherwise robust disaster risk management approach can remain highly exposed to financial shocks, either to the government budget or to groups throughout society"*.

While guaranteeing social assistance, governments should at the same time encourage private initiatives in prevention and financial protection. As emphasized by OECD (2015), improving public awareness reduces the human-induced factors that make a major contribution to the cost of disasters and alleviates losses on public finances. In particular, since private insurance is the main risk financing tool for businesses and households, the OECD (2012) recommends that governments *"assess* *their availability, adequacy and efficiency to the population and within the economy, as well as their costs and benefits relative to other types of possible risk reduction measures"*.

A series of challenges hinder the development of the insurance business in protection from natural disasters. First of all, Kousky and Cooke (2012) shows that spatial correlation creates the potential for enormous losses at the aggregate level, and insurers therefore need to access a large amount of capital in order to offer the cover and meet solvency constraints. Consequently, they are often forced to drive up premiums, which could become so high that it would not be rational for individuals to purchase the policy. Large insurers can significantly reduce the probability of insolvency by pooling risks from more independent regions or by transferring a portion of their portfolio through reinsurance. However, while lowering premiums for regions with a higher risk, this solution might raise those of those with a lower risk and, especially in a competitive market, low risk-individuals might fail to purchase, therefore leaving the company with an extremely risky pool. As shown by Charpentier and Le Maux (2014), the free market does not necessarily provide an efficient level of natural-catastrophe insurance, but government-supported insurance allows losses from disasters to be spread equally among policyholders thanks to the government's easier access to credit.

Climate change also exacerbates these issues: the Geneva Association (2013) warns that return periods and correlation among claims for several high-loss extreme events are *"ambiguous rather than simply uncertain"*, and raises concerns about the future sustainability of insurance business on natural risks. Social assistance policies may also hinder the development of private markets and increase the financial burden of natural disasters on public finances due to charity hazard (World Bank, 2014).

Against this background, a number of economies have established various forms of public-private co-operation to support the insurance business, and several countries have decided to enter the market by establishing a public-private company entirely devoted to insuring citizens' properties against natural disasters at a discounted price (e.g. Spain, France, Australia, Turkey, New Zealand, Taiwan, USA, etc..). This strategy helps to strengthen the resilience of a community by promoting the development of the insurance sector and allowing faster recovery (Hallegatte and Przyluski, 2010).

The aim of this thesis is to investigate the role of public-private partnerships in insurance for the management of natural disasters. Chapter 2 reviews the international experience and investigates the main weaknesses of the systems currently in force. We analyze the Government's perspective and we extend the existing literature by broadening the attention to a wider number of stakeholders, rather than describing a two-side relationship between the private insurers and the public bodies. The aim of this work is in fact to investigate how public authorities can build society's resilience along with the overall community by agreeing and designing a set of coherent actions that (1) protect the well-being of citizens; (2) allow the achievement of the general development objectives; (3) protect the private sector; (4) do not unduly weaken public resources. In addition to the need to further invest in risk understanding, the main problem encountered is weak governance. In particular, the management of natural disasters has often not been included in the Countries' development plans, and therefore risk reduction initiatives often collided with urbanization and development choices. Uncontrolled development and climate change are actually increasing natural risks faster than countries are able to reduce them, and it is therefore important to switch to a more inclusive approach.

The following three chapters are devoted to the Italian case study and progressively define a public-private insurance scheme for earthquakes and floods. Italy is in fact highly exposed to natural risks, especially earthquakes and floods, but there is currently no well-defined loss allocation mechanism at national level. A few people insure their properties (Maccaferri, Cariboni, and Campolongo, 2012) and expect social assistance from the government instead. Each natural event is evaluated by public authorities when it occurs, social assistance depends on the decisions of the parties in charge and is therefore commensurate with the financial resources available at the time. In recent years public debate has increasingly shifted towards natural risk management and planning, although at the moment no initiative has been undertaken. In defining the public-private insurance scheme for Italy, this thesis addresses three issues, each covered in a specific chapter.

Chapter 3 estimates expected loss in case of lack of data on past losses. Insurance companies need big loss database for premium rating, but there is currently no source that collects information on natural impacts in Italy at national level. Lack of data on the impacts of natural disasters is a widespread issue and in order to overcome this problem, the world's biggest insurance companies have developed sophisticated models for loss estimation based on engineering and geology studies. In this chapter, we propose new techniques for measuring risks when historical data lack. In particular, we refer to a previous model for the estimation of earthquake losses, to which we introduce a more detailed representation of the probability of earthquakes occurring. An alternative approach is proposed for floods and our method contributes to the literature because we are dealing with both lack of detailed information on the characteristics of the basins as well as the scarcity of historical data. While better accuracy of the estimates is desirable for the future, our models provide a first quantification of losses at the individual and local level that allows the relevant authorities to better appreciate the riskiness of the territory and set the basis for the construction of a public insurance system.

Once losses have been estimated, Chapter 4 proposes the public-private insurance model. Our model departs from the existing literature by addressing a public-private partnership, which therefore modifies the fundamental hypotheses of traditional insurance. Our contribution to the literature can be summarized in three aspects. First, the purpose of the business is social assistance, and premium collection serves solely to risk management and to guarantee quick compensation to the damaged population. Therefore, rates do not include any profit load and are commensurate to citizens' demand. Second, we introduce the government as a social guarantor that contributes to reserves and provides public funds in case reserves are not sufficient for claim compensation. Finally, our model includes spatial correlation by applying the Hoeffding bound for r-dependent random variables.

Chapter 5 extends the insurance model to multi-hazard management. As well known in finance, merging risk portfolios is beneficial only if risks are uncorrelated, as floods and earthquakes are likely to be. It remains to be seen whether the benefits from risk diversification counteract the negative impact of spatial correlation.

Each of these three chapters presents and discusses the relative results. We found that seismic risk produces the highest expected losses at national level, but floods may generate the highest losses per square meter. The two perils differ in geographic extent: while the seismic risk involves almost all the nation, floods concern approximately two thirds of the territory. Though the seismic risks generate expected losses that are almost six times greater than floods, we found that the amount of public funds needed to manage them is almost the same. Our analysis shows that the public-private insurer can benefit from risk differentiation by jointly managing earthquake and flood risks through a multi-hazard policy: the amount of public capital needed is lower than would be necessary if the two risks were managed separately. Another desirable feature emerges: rates for multi-hazard policies are more geographically homogeneous, and therefore promote fairness perception among the population. However, it emerged that under no circumstances does the maximum premium that individuals are willing to pay match the insurer capital constraints. Without the government as a guarantor, it would therefore be impossible for the company to offer policies throughout the whole territory.

Chapter 6 concludes the thesis and presents some works in progress that were born from this project.

Chapter 2

A review of public-private partnerships for natural risk management

The full text of the article is also available from the arXiv repository, preprint number 2006.05845.

Abstract

This chapter reviews the role of public-private partnerships in the management of natural risks, with particular attention to the insurance sector. We show that four elements are necessary for them to be effective: strong government financial support, a great commitment to risk reduction, high citizen participation and ongoing access to the reinsurance market. Poor risk knowledge and weak governance have widely challenged these initiatives during the recent years, while the future is threatened by climate change and unsustainable development. We argue that a greater involvement of all segments of the community, especially the weakest layers, is needed and the management of natural risks should be included in a sustainable development plan.

2.1 Introduction

Natural risks pose a broad range of social, financial and economic issues, with potentially long-lasting effects. Historically, governments have mostly addressed the financial effects of natural events on an ad-hoc basis, but, since the 1970s, a strong awareness-raising activity by the United Nations has profoundly changed the attitude of the national authorities.[1] According to the United Nations, the activity of governments should not just be limited to guide citizens toward recovery in the aftermath of an event but should rather prepare them and create the conditions necessary to ensure rapid resilience. To this aim, OECD, G20 (OECD, 2012), the World Bank and GFDRR (World Bank, 2014), encourage countries to adopt a comprehensive disaster risk management strategy, which should be articulated in a series of coherent and coordinated actions, well distributed and defined over time and aimed at addressing each phase of a disaster. In particular, a strategy should include risk assessment, risk reduction, preparedness, emergency response, and recovery.

Among these phases, all equally important, risk reduction is by far the most complex to plan. Many tools able to reduce the financial impact of natural events exist and can be divided into three categories based

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[1] The United Nations dates the beginning of the global disaster risk reduction process to the International Expert Group Meeting in July 1979, but the first International Framework of Action - the international Decade for Disaster Reduction - began 10 years later, on January 1990. Then framework has then been followed by the Yokohama Strategy in 1994. In 1999 the United Nations established the UNDRR (United Nation office for Disaster Risk Reduction), a secretariat dedicated to facilitating the implementation of the "International Strategy for Disaster Reduction". The office presented a first plan - the "Hyogo Framework for Action 2005-2015" (United Nations, 2005) - to explain, describe and detail the work that is required from all different sectors and actors to reduce disaster losses. When the framework reached maturity, a 15-year-long, voluntary, non-binding agreement aiming at "*the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries*" - the "Sendai Framework" (UNISDR, 2015) - was adopted by UN Member States. A series of agreements - the 2030 Agenda, the Paris Agreement on climate change, the New Urban Agenda, the Addis Ababa Action Agenda and the Agenda for Humanity - then sought to coordinate risk reduction with the other global challenges. Other international organizations are also involved in similar projects for the prevention, mitigation and management of natural disaster risk, such as ADB (Asian Development Bank), FAO (Food and Agriculture Organization of the United Nations), OECD (Organization for Economic Co-operation and Development) and the World Bank. For example, in 2012, G20 Finance Ministers and Central Bank Governors, along with G20 Leaders mandated the OECD to develop a voluntary framework for strengthen disaster risk assessment and financing (OECD, 2012).

on how the risk is addressed. We distinguish between risk mitigation, risk retention and risk transfer. Risk mitigation acts on the physical and environmental conditions responsible for the financial impact, therefore all structural interventions aimed at decreasing the probability of an event occurring (e.g. reservoirs), the vulnerability of exposed assets (e.g. retrofitting on private homes) or the number of goods and individuals exposed (e.g. restricting building permission in high-risk areas) fall into the first category. Since risks cannot be completely mitigated and structural interventions might not be cost-effective (Hudson, Botzen, et al., 2016), a good risk management strategy should always include some degree of financial protection (World Bank, 2014). Financial instruments[2] for risk reduction can distribute the costs over time by accumulating sufficient capital to face the expected losses of future events (risk retention), or transfer the risk to specialized subjects, i.e. insurers and reinsurers, or to the market through catastrophe linked securities. Both risk retention and transfer facilitate emergency response and speed up recovery by providing resources in the immediate aftermath of an event.

The governments not only should select and adopt the most suitable risk reduction measures but must also ensure that individuals have access to them. Since private insurance on buildings and/or on other movable assets is the main risk financing tool for businesses and households, the OECD (2012) recommends that governments *"assess their availability, adequacy and efficiency to the population and within the economy, as well as their costs and benefits relative to other types of possible risk reduction measures"*. Nevertheless, a series of market failures endanger financial and insurance markets[3] and makes it necessary to further reduce the risks

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[2] Two approaches to risk financing exist and correspond to different financial instruments. Risks might be addressed ex post by means of existing resources and powers, or ex ante with financial mechanisms explicitly arranged or secured beforehand. For example, ex ante instruments that governments can rely on are reserve funds, contingent credit facilities, re/insurance, catastrophe-linked securities. Examples of ex post financing are budget reallocation, debt financing, borrowing and taxation. Note that ex post financing does not preclude the establishment of institutional arrangements that specify, ex ante, the government's financial commitments (OECD, 2012).

[3] Main market failures in disaster risk management relate to the insurability of risks, information asymmetry, adverse selection, consumer behavior, moral hazard and charity hazard. As far as insurability concerns, spatial correlation among insured assets constitutes a central issue for disaster management because generates the potential for enormous losses to the insurers (Glauber, 2004). For example, a series of hurricanes in the US during the 1990s led to a consistent number of insolvencies (Matthews et al., 1999; Mills, Lecomte, and Peara, 2001). As a consequence, insurance included higher risk-load in premium rating for high-risk areas (Feldblum, 1990; Kreps, 1990; Meyers, 1996; Mango, 1997; Mango,

before transferring them. In this respect, governments have often intervened by investing in risk mitigation and increasing public awareness among the population. In some cases, the costs of policies were prohibitive for some segments of the population, and the authorities directly intervened in the insurance market by establishing a public-private partnership. Though in some circumstances efforts of governments have already been substantial, the Geneva Association (2018) expects the role of the insurance industry to become increasingly relevant in the next future and urges governments to increase their commitment in monitoring socio-economic risks of climate change, developing risk management plans for all sectors of the economy, and establishing relevant public-private partnerships with insurers to enhance socio-economic resilience.

The fragility of the insurance industry is only part of the complex issues that countries face. Governments themselves are in fact significantly exposed to disaster risk: public exposures are large, including human losses, injuries, damage to public goods, tax pressures resulting from financial commitments and unplanned post-disaster financial assistance, as well as potentially negative changes in macroeconomic conditions such as possible lower economic growth or lower tax revenues.[4] In order to protect the national financial stability, the Sendai Framework claims that the government, while guaranteeing social assistance, should share responsibilities with private stakeholders and therefore private initiatives in prevention and financial protection should be encouraged. As emphasized by the OECD (2015), improving public awareness reduces the human-induced factors that make a major contribution to the cost of disasters and alleviates losses on public finances. However, educating and informing the society is usually not enough.

fHence, if some degree of government involvement is necessary to

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1998; Kreps, 1998), that often do not meet the demand from rational purchaser (Kousky and Cooke, 2012). Along with behavioural bias (Kunreuther, 1996), climate change further complicates the development of financial and insurance market. The Geneva Association (2013) warns that return periods and correlation among claims for several high-loss extreme events are "*ambiguous rather than simply uncertain*", and raises concerns about the future sustainability of insurance business on natural risks. Failures in capital markets have been explored by Froot (2001), that found that securitization is not always the lowest-cost way to transfer risk due to supply restrictions associated with capital market imperfections and market power exerted by traditional reinsurers.

[4] Losses that the government may incur can be both explicit or implicit: the expenses that could derive from the reconstruction of public goods and infrastructures or other financial commitments following a disaster are explicit; on the contrary, expenses that do not reflect any type of commitment or liability, but which can still occur due to a perceived obligation are implicit.

protect the most vulnerable layers of the society and the market, how can authorities balance public and private initiatives? According to Jaffee and Russell (2013), public initiatives should only complement private activities and the role that the government should assume depends on the relationship between objective and subjective probabilities of loss. In case of perfectly rational individuals with objective perception of risk, an active role of government is necessary during emergency response only; if individuals underestimate their risk, investments in public awareness are needed or, alternatively, mandatory insurance purchase might be introduced. Whether other differences between objective and subjective probabilities are not generated from behavioural biases, the government should identify and implement the solution that addresses the specific market failure in the most efficient way.

Unfortunately, identifying market failures is complicated. To make matters worse, "*with increasing complexity and interaction of human, economic and political systems within ecological systems, risk becomes increasingly systemic*" (UNDRR, 2019), and responsibilities increasingly blurred. In increasingly uncertain and complex contexts, cooperation between all the subjects involved - individuals, businesses, authorities - is essential to build a community's resilience (Surminski and Hudson, 2017). It is therefore important that the Government is able to create and coordinate a coherent and clear system of actions and responsibilities, which pursues development and well-being goals shared by all stakeholders. To this end, the public sector should be able to balance its intervention with the activity of the private sector, in order to protect the stability of both but at the same time allowing the whole community to achieve an adequate level of protection and security.

Although most countries are still not adequately prepared to deal with the consequences of possible future disasters[5], some have already implemented a public-private partnership with the insurance sector. Almost all these few countries have intervened in the insurance sector, becoming insurers, reinsurers or, in the poorest economies, by activating micro-insurances. Some survey on these partnerships have already been published, and we refer to those for a more detailed discussion of the different case studies (e.g. Paudel, 2012; McAneney et al., 2016; Hudson, Ruiter, et al., 2020). In this review we analyze the Government's perspec-

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[5] According to the report by Wilkinson et al. (2017), a number of disaster risk management activities were conducted during the past decades (most of which were relatively low cost), but, however, they were not as effective as they could and disaster losses increased during the Hyogo Framework of Action.

tive, and we broaden our attention to a wider number of stakeholders, rather than describing a two-side relationship between the private insurers and the public bodies. The aim of this work is in fact to investigate how public authorities can build society's resilience along with the overall community by agreeing and designing a set of coherent actions that (1) protect the well-being of citizens; (2) allow the achievement of the general development objectives; (3) protect the private sector; (4) do not unduly weaken public resources.

To this aim, we begin with a brief discussion of the main type of public-private partnerships currently in force in the next section. The benefits of these partnerships are widely recognized, but some important weaknesses have also emerged. Among these, risk understanding and government's attitude toward natural risks are today the two major limits in disaster risk management, which we discuss in section 2.3. In section 2.4 we argue that many of these weaknesses can be overcome by adopting a more inclusive approach - namely a community-based risk management approach UNDRR (2019) -, which involves a greater number of stakeholders and therefore allows to monitor the risk on the whole society. To conclude, section 2.5 discuss the future challenges in disaster risk management.

2.2 Public-private partnership in insurance

There is a widespread agreement on the benefits of public-private partnerships for the management of natural disasters (Kunreuther, 2006b; World Bank, 2012b; Shukla et al., 2019) and in particular, public intervention in the insurance sector is increasingly proving to be effective, especially in the poorest countries. Government-supported initiatives are in fact able to distribute risks and losses over the entire population and over time (Kunreuther and Pauly, 2006), and are much more flexible than private solutions as they are not tied to profit objectives (Penning-Rowsell, 2015). Moreover, they help to strengthen the resilience of a community by promoting the development of the insurance sector and allowing faster recovery (Hallegatte and Przyluski, 2010). When insurance schemes are properly designed and supported, they communicate risk to the population, foster adaptive responses and risk reduction and above all improve economic stability and protect the well-being of the community (Kunreuther and Pauly, 2006; Lotze-Campen and Popp, 2012; Hudson, Botzen, et al., 2016; Kunreuther and Lyster, 2016; Kousky, Michel-Kerjan, and Raschky, 2018; Linnerooth-Bayer, Surminski, et al., 2019). As argued by Bruggeman, Faure, and Fiore (2010), however, public intervention are beneficial only if they solve a specific market failure that the private sector is not able to cope with on its own. Otherwise, the State's entry into the insurance (or reinsurance) market might play a distorting effect. Unfortunately, identifying and recognizing the market failure may not be easy.

Provided that the public intervention is necessary, the effectiveness of the insurance system depends on a number of conditions. First of all, it is essential to achieve a satisfactory understanding of the natural phenomenon and the extent of the losses to which it can lead. In particular, capturing the spatial correlation that binds insured properties is fundamental as it challenges the rating process and, in turn, the financial stability of the system, as happened for example in the U.S. corn insurance market (Woodard et al., 2012). Secondly, the business should be supported by a coordinated set of actions aimed at overcoming all the frictions that generate low take up rates, such as lack of trust in the institution, liquidity constraints, and limited salience among citizens (Cole, Giné, et al., 2013). Educating the population has often fostered the adoption of policies (Bogale, 2015; Gan, Jarrett, and Gaither, 2014), and income and development support measures proved effective in some circumstances (Greatrex et al., 2015; McIntosh, Sarris, and Papadopoulos, 2013). If this is not sufficient, mandatory insurance purchase tackles the root problem (Kunreuther and Pauly, 2006), though this solution may not be well received by citizens. Furthermore, raising awareness of the population on natural disasters in quiet periods is also decisive, as the prolonged absence of major events leads to lowered attention and decreases policy's purchase (Gan, Jarrett, and Gaither, 2014; Gallagher, 2014).

In this section we present and discuss the three fundamental types of public-private-partnership in the insurance business - public insurance, public reinsurance, and micro-insurance -, how governments have implemented them and the difficulties they encountered.

2.2.1 State-owned insurance companies

When a peril has a potential high economic impact in a given area, insurance companies are concerned about their financial stability and therefore decide to limit the offer or to provide coverage at an excessively high price in that area. If the area is large and the number of individuals and uncovered properties is high, the lack of insurers becomes a huge problem for the government as citizens might demand for public intervention in the aftermath of an event. When facing this situation, some countries reputed offering policies at a price affordable for all citizens more efficient than deploying capital in ex post relief programs (Kunreuther and Pauly, 2006) and have therefore established a state-owned insurance company. As public companies aim at solving gaps, coverage is provided for perils that cannot be borne by private companies only. In fact, most of the schemes deal with a single peril, such as earthquakes in California or Turkey, or with a restricted set of them. Insurable items are also limited: coverage is usually provided only for buildings, sometimes even for vehicles, while other risks, such as business interruptions, are rarely covered.

Table 1 describes the main public insurance against natural disasters currently in place. Most of these companies were born out of heated debate between insurers operating in the area and the national authorities and are supported by both. Sometimes the role of the private sector is limited to technical advice during the creation of the public program and to data provision, other times the public company shares the risks with the private ones through co-insurance. Furthermore, private companies almost always act as intermediaries between citizens and the public company by underwriting policies and transferring risks and the related premiums to the state-owned entity in exchange for a fee. Governments typically support the public company by assuming the role of guarantor in exchange of a charge (e.g. EQC in New Zealand) or for free (e.g. Consorcio de Compensacion de Seguros in Spain). Alternatively, governments may provide a prearranged facilitated access to credit, as in the case of the National Flood Insurance Program (NFIP). In addition, State-owned companies may also benefit of contingent credit lines from international organizations such as the World Bank.

Since the main purpose of government pools is to give the chance to most of the population to get insured, the policies are sold at a low price or at least at a premium lower than that offered by private companies. The main reason why public insurance companies may charge lower rates is that, unlike private companies, they do not have to distribute profits. However, this choice has some important drawbacks. First, the low premiums of the public insurer can compete with the few private companies that have decided to offer the policy, generating a crowding out effect and weakening the private sector (McAneney et al., 2016). Second, if low rates are not actuarially sound, they expose public insurers to a risk of reserve depleting higher than that legally allowed to traditional insurers. Furthermore, in a competitive market, the transaction and administration costs that public companies have to bear can be even higher than those of the corresponding private companies (Marshall, 2018; Michel-Kerjan, 2010). In addition, governments often apply flat premium rates that include subsidy among individuals but fail to create risk-reflecting reserves. Low rates therefore make government guarantees or other forms of public financial support necessary to the sustenance of the program but, in order to limit public capital injections, the pool should ideally become self-sustained at a certain time. To this aim, governments can reduce the risk beared by the company by encouraging and committing communities to risk mitigation (Kunreuther, 2006a; Kunreuther, 2015). Building codes and premium discounts for properties subjected to structural strengthening interventions have been extensively adopted, albeit with varying results. The risk reduction is in fact largely demanded to citizens, who may consider the investment not advantageous (Kleindorfer, Grossi, and Kunreuther, 2005), and therefore countries that have applied more binding risk mitigation plans have obtained greater participation.

Some comparative analysis on Switzerland and Germany have shown that establishing a public insurance monopoly can significantly increase the system's self-sustainability. In fact, monopoly lowers the transactional and administrative expenses by eliminating the need for insurance brokers and agents and allowing the company to keep a rather simpler service. At the same time, it encourages the company to invest in risk reduction not just in terms of the amount of expenditure, but by promoting a more effective planning too (Ungern-Sternberg, 2001; Kirchgaessner, 2007). Unfortunately, the establishment of insurance monopolies is severely hampered by the private sector and by some constraints in current legislation (e.g. the EU bans these monopolies, and Germany was forced to dissolve its one in 1994).

The company's financial exposure can then be reduced by applying deductibles to the policies or transferring the risks through reinsurance. Both components are important: the former preserves a certain degree of citizens' responsibility; the latter allows the State-owned company to get rid of the higher losses by transferring them to specialized bodies or on international markets, so as not to unduly affect the insurance reserves and public resources following a catastrophic event (OECD, 2018b). In particular, as risks evolve rapidly and disasters become more and more frequent, reinsurance is essential for public companies to survive (Seo, 2004).

Although all the schemes in Table 1 are profoundly different from each other, any of them requires four elements to properly function: strong government financial support, a great commitment to risk reduction, high citizen participation and ongoing access to the reinsurance market. Since State-owned insurances are just a few and some of them are extremely young, it is difficult to outline how to properly balance the four components. However, the history of NFIP, which is one of the oldest and most studied public insurance programs, has shown how decisive these components are.[6]

Voluntary citizen participation is the most common issue in natural disaster insurance, and, despite favorable cost, most State-owned insurances record low take up rates also. Undesired consequences of low insurance penetration are potentially high costs of government's post-disaster assistance (Dixon et al., 2006), and reduced access to the reinsurance market for the insurer (von Lucius, 2004). There are several reasons why the population exhibits careless behavior towards natural disasters' prevention, but state-owned insurances seem particularly affected

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[6] NFIP is a public insurance program for flooding in the U.S. and provides policies only if the community joined a floodplains laws and ordinances program. The program applies risk-based premiums (although some subsidy was introduced in 2014 with the Homeowners Flood Insurance Affordability Act) defined on the flood maps. In order to better capture the real risk of the different areas, the government committed to update and complete the flood risk maps. The program has been hardly criticized because rates did not provide the necessary income to build long-term reserves (US General Accounting Office, 2001) and flood mapping process was not so effective and timely as planned (Kousky and Kunreuther, 2014). In addition, NFIP was not authorized to secure private reinsurance until the Biggert-Waters Flood Insurance Reform Act of 2012 and the Homeowners Flood Insurance Affordability Act of 2014. Although rates have been updated several times, the program reached the statutory borrowing cap from the Treasury in September 2017. The U.S. Congress cancelled more than half of the debt, but NFIP had to borrow additional capital two months later. The company's outstanding debt is currently $20.5 billion and is likely to grow as its annual probable maximum loss is over $40 billion and its capacity to pay claims without borrowing is $5.4 billion (FEMA, 2020). As extreme rainfall along the Gulf Coast are on the rise (Oldenborgh et al., 2017), it therefore seems very unlikely that the program will be able to resist without the strong support of the State. Moreover, unless reauthorized or amended by the Congress, the NFIP's borrowing limit from the Treasury will be reduced from $30.425 billion to $1 billion at the end of September 2020. Although late access to reinsurance and low premiums have certainly played a role in the NFIP's debt accumulation, part of the financial weakness of the program is due to the insufficient participation of the communities. In general, individuals have not invested enough in risk mitigation and the government has not been able to identify the right stimuli. A more frequent remapping and the consequent adjustment of the premiums could have helped to spread awareness and encourage private investments (Michel-Kerjan, 2010; Kousky and Kunreuther, 2014). Along with insufficient risk mitigation, NFIP has also recorded low take up rates (Dixon et al., 2006).

by charity hazard (Gurenko et al., 2006; Raschky and Weck-Hannemann, 2007; Başbuğ-Erkan and Yilmaz, 2015; Marshall, 2018). The belief that the government will help irrespective of owning an insurance policy is stronger when governmental relief is more certain (Raschky, Schwarze, et al., 2013), and States offering a public-private insurance have usually been very generous to the community when hit by a disaster. Along with charity hazard, low risk perception and poor policy understanding are also quite frequent (Chivers and Flores, 2002). Introducing mandatory insurance purchase can rise take up rates (Kunreuther and Pauly, 2006; Kriesel and Landry, 2004), provided that the obligation is properly formulated and monitored (Dixon et al., 2006). For example, in Turkey, property-owners are required to prove to have valid policy only when they want to buy or sell a house or to obtain a new account for water and electricity services. As argued by Başbuğ-Erkan and Yilmaz (2015), this sporadic check does not enforce ongoing renewal of the insurance. The Turkish government has therefore activated some initiatives aimed at promoting awareness, many of which have been designed so that the most sensitive citizens involve an increasing number of acquaintances. For example, a 20 percent premium discount is offered if eight individual apartment unit owners from the same apartment complex jointly take out a policy, and is supporting the growth of a large volunteer and civil society network (Başbuğ-Erkan and Yilmaz, 2015; World Bank, 2019). As frequent monitoring mandatory requirement might be expensive, extending the policy validity to multi-years might also help (Michel-Kerjan, Forges, and Kunreuther, 2011; Kleindorfer, Kunreuther, and Ou-Yang, 2012).

Along with scarce participation of the citizens, State-owned companies should also deal with all the problems traditionally affecting insurers. First of all, adequate risk assessment might be extremely challenging where historic losses are not available. An insurance scheme might be hence designed based on simulation techniques, as in the case of the Turkish Catastrophe Insurance Pool (Linnerooth-Bayer, Mechler, and Hochrainer-Stigler, 2011), but this brings additional uncertainty to the estimates (Başbuğ-Erkan and Yilmaz, 2015; Cakti, Erdik, and Sesetyan, 2006). The sensitivity of the cost of reimbursements to changes in market prices or the reconstruction of homes should also be considered when constructing reserves. For example, in New Zealand, the State-owned insurance EQC operates in co-insurance with the private sector and pays its reimbursement quota to the insured along with the traditional insurer. After the Christchurch earthquake sequence in 2011, different private companies met their obligation at different times (some even took more than 5 years) and, since the reimbursement provided by EQC is equal to the cost of rebuilding the home, the cost of the event on the company's reserves was strongly affected by the market price variation of both construction works and materials (Wood, Noy, and Parker, 2016).

2.2.2 Public reinsurance companies

Some countries faced great natural risks with an underdeveloped insurance industry that was not solid enough to manage the potential losses of the entire population. In order to strengthen the private insurance sector and foster its growth, a few governments established a State-administered reinsurance company to which insurers can or must transfer natural risks (some examples are reported in Table 2). Like public insurance, governments often ease the financial pressure of public reinsurer by assuming some layer of risk - e.g. as a guarantor of last resort. However, compared to providing a State guarantee to insurers, this strategy preserves individual responsibilities and requires the participation of all individuals who contribute to the creation of the financial exposure as the cost of reinsurance is charged on the final price of the policy (Bruggeman, Faure, and Fiore, 2010).

The characteristics and problems of public reinsurance are very similar to those of State-owned insurances. First, the premium paid for reinsurance is typically low because the authorities want the insurers to keep citizens' premiums low. However, in this case, this solution is disproportionately beneficial for private insurers which are free to apply the rating mechanism they want. For this reason, some government-reinsurers fixed the property-owners' premiums by legislative decree and/or obliged insurers to offer the policy. In particular, policies for natural disasters are often compulsorily included in other basic policies, the purchase of which may be mandatory for property-owners. In general, this has led to satisfactorily high insurance penetration rates, and thus outperforming public insurers in terms of take up rates. On the other side, low reinsurance premiums may also challenge the company's financial stability, as happened to the French Casse Centrale de Reassurance (CCR) in 1999.[7]

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[7] In France, the publicly owned reinsurance company Casse Centrale de Reassurance (CCR) hit bankruptcy in 1999 due to too low fees and too much confidence in the unlimited State guarantee (Vallet, 2004; Bruggeman, Faure, and Fiore, 2010). Measures were then taken which changed the conditions of the subscription. There is also concern for the young

In order to ease financial pressure, governments often include risk mitigation in the State's risk management plan, although the measures envisaged have not always been effective. In addition to the difficulties in incentivising private investments in risk reduction, the government's management objectives strongly hindered risk reduction in many countries. In France, for example, when the mandatory insurance requirement came into force and the CCR was instituted, the flood risk mitigation measures required clashed with the growth interests of the local authorities and consequently were not implemented properly (Vallet, 2004). In the UK, instead, the government does not seem to actually encourage risk reduction despite it signed its commitment in the agreement with the insurers (Surminski and Eldridge, 2014; Penning-Rowsell, 2015; Surminski, 2018). In Florida, the Florida Catastrophe Insurance Fund was launched to encourage urban growth but, according to Seo (2004), this increased the risk exposure over time, powered by climate change. In 2009, to decrease exposure, the government has hence activated a program for gradual privatisation of its risk, which also introduced the adoption of retrocession lines and insurance-linked securities (ILS). In this respect, retrocession is proving increasingly important to ensure the continuity of public reinsurance due to climate change and the slow progress in risk mitigation.

To date, the strength of probably the most stable public reinsurance system in place, the Japan Earthquake Reinsurance Co., is due to a combination of all the revised elements: an adequate risk preparedness and mitigation, a strong political leadership, a structured risk retrocession plan, and the simplicity of the policies that has favored adoption by citizens (Takeda, 2004).

2.2.3 Micro-insurance

In the poorest countries, natural disasters generate far more complex social issues than in developed ones, such as malnutrition, school dropouts, increased poverty. Moreover, the risk of natural disasters can slow down the development of these countries, as farmers are more reluctant to invest in new cultivation techniques that can potentially boost productivity in the long run but might generate greater loss in case of a disaster (World Bank, 2014). In these contexts, insurance can help safe-

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Flood Re in the UK, which seems to generate strong pressure on public finances (Surminski, 2018).

guarding productivity and, potentially, economic growth. However, the poorest have hardly access to risk transfer.

The reasons for the low (or absent) penetration of insurance markets in this segment of the population are manifold and are only partially related to the supply side. In fact, if on the one hand the insurers often fail to assess the risk in these territories due to the lack of historical data, on the other the individuals are very reluctant to purchase. Several studies on African and Asian regions have in fact brought to light a strong distrust of population towards the companies that offer insurance or the institutions that support them (Cole, Bastian, et al., 2012; Greatrex et al., 2015).

In this complex context, international organizations, especially the World Bank, and local or national governments have begun to adopt several form of micro-insurance, especially index-based insurance. An index-based (or index-linked) insurance is an insurance policy whose payout is triggered by an easily-measured event, represented through an index, typically concerning weather conditions (e.g. rainfall below a certain level). Index-based insurance are usually applied to agricultural risks and many initiatives have been activated by local governments in several regions of Africa and Asia. A great advantage of these tools is that they do not need information on individual losses, but only weather or environmental data which are more easily available and less expensive to monitor. For the same reason, the compensation mechanism is far more transparent, thus preventing moral hazard and facilitating the access to reinsurance market for the insurer (Alderman and Haque, 2007; Cole, Bastian, et al., 2012).

The main issue related to index-linked insurance is basis risk: it is possible that an individual receives a payment when he has not suffered losses or that he does not receive it against a large loss. In this regard, various solutions for fine tuning indexes have been proposed in the literature, the main ones being the use of early warnings and seasonal forecasting in the payout triggering mechanism and the definition of complex indices incorporating multiple climatic measurements and built on a better geographical granularity (Rao, 2010; Daron and Stainforth, 2014; Dercon et al., 2014; Conradt, Finger, and Spörri, 2015). Another unfavorable drawback generated by basis risk is that it reduces consumer demand for insurance.

On the demand side, however, frictions are related to non-economic factors, including levels of financial literacy, liquidity, distrust (Cole, Bastian, et al., 2012; Eling, Pradhan, and Schmit, 2014; Bogale, 2015; Greatrex et al., 2015). Cole, Bastian, et al. (2012) found a positive effect of involving non-governmental organisations on take up rates, though the impact differs depending on their reputation. The organisation staff might help overcoming distrust and spreading knowledge of the products. Investing in financial literacy and training courses is also highly recommended (Cole, Bastian, et al., 2012; World Bank, 2005), though empirical evidence is confusing (Binswanger-Mkhize, 2012; Cole, Bastian, et al., 2012; Bogale, 2015).

In addition to the difficulties in defining the instruments and the poor grip on the demand, other factors challenge the future of index-linked securities. First, many of these initiatives are supported by the authorities through vouchers or remittances and this support is essential to allow the establishment of the insurance scheme. However, if the system fails to develop properly and does not become profitable to the provider, it is likely that the insurer will stop offering the policy (Alderman and Haque, 2007). Further uncertainties concern the future affordability of the policies. Siebert (2016) notes in fact that the premiums in the Sahel region are extremely sensitive to the climatic parameters of the model and this could lead to a considerable increase in prices in high-risk areas - an increasingly likely scenario, given the strong effects of climate change on weather events. Hence, in order for micro-insurance to continue, an effort from the public sector is still needed (Cole, 2015). Governments will have both to invest in facilitating access to risk transfer to the poorest, and to incentivize companies to keep offering policies and innovate index-linked insurances.

2.3 Failures

Some theoretical study show that public-private partnerships are able to offer a more efficient level of natural-catastrophe insurance than free markets (Burby, 2001; Charpentier and Le Maux, 2014) but a series of deficit characterizes the history of government pools. In this respect, McAneney et al. (2016) argues that "*Government pools usually contain an inherent contradiction in trying to provide low cost insurance to high-risk properties and so the funding of deficits to which they are inevitably prone becomes important*". Fat-tails and spatial correlation make aggregate losses extremely volatile and also contribute to insolvencies (Kousky and Cooke, 2009; Kousky and Cooke, 2012). Moreover, most of the government supported insurance apply flat premium rates that do not reflect the asset's riskiness. This choice may be motivated by economic arguments (Hallegatte, 2011), but might fail to provide the necessary income to build long-term reserves.

Public-private insurers can in principle minimise losses by encouraging risk mitigation (Kunreuther, 2006a; Kunreuther, 2015), but little evidence about this can be found in practice. In particular, insurance companies try to encourage risk mitigation by offering discounted policies. However, in order for this initiative to be successful, insurers must have the opportunity to apply risk-based premiums (Kunreuther, 2015) or, if the government demands a form of subsidy in the rating, the authorities must actively engage in risk mitigation, for example by outlining well-enforced building codes that force property owners to adopt cost-effective protective mechanisms (Kunreuther, 2003). However, defining effective rules on construction and policy purchase and enforcing them has often proved practically difficult and not always in line with the other management objectives of the local authorities.

Alternatively, strengthening the business by adopting new forms of reinsurance coverage can protect insurers against potential insolvency from disasters too (Kunreuther, 1996; Lee and Yu, 2007) and for this reason the ILS market has significantly grown in the last decades (Cummins, 2007; Cummins, 2008; Cummins and Barrieu, 2012). Despite this, the ILS market is still relatively young and countries are often reluctant to adopt these securities because they usually lack experts who can oversee their construction and issuance (OECD, 2010; Michel-Kerjan, Zelenko, et al., 2011).[8] In addition to lack of technical knowledge, the development of the ILS market could also be hindered by the crowding out effect[9] that governments involved in the free market exert on more efficient private reinsurance solutions (Cummins, 2006).

According to UNDRR (2019), to date countries have "patchy" implemented their risk management strategies. Most are addressing the consequences of disasters rather than trying to reduce their actual risk. The great weaknesses of the national strategies currently in place and the reasons that led to a too slow development of proactive strategies at the na-

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[8] In order to incentivize the adoption of catastrophe-bonds, in 2009 the World Bank has launched the MultiCat program, in which it offers its technical support and act as an arranger. In the same year, Mexico benefited from the program and issued a US$290 million cat bond with a three-year maturity (World Bank, 2013).

[9] The crowding out effect of public programs refers to all those situations in which government-supported initiatives meant to cover the uninsured prompt those already enrolled in private insurance to switch to the public program.

tional level can all be traced back to two major problems: insufficient risk understanding and weak governance (Opitz-Stapleton et al., 2019).

2.3.1 Risk understanding

The effectiveness of risk management policies strongly depends on the ability to identify and assess the risks (UNISDR, 2017). Knowing the probability of occurrence of the events and their potential impacts[10] constitutes the basis for developing and evaluating the whole range of risk management strategies, such as emergency plans or cost-benefit analysis[11] of risk reduction measures. It also allows the decision-making process to develop skills to be adapted to local risk profiles and the social conditions of the communities involved, promoting awareness of potential risks among the society. A well-established collection of data on risks, exposures, vulnerabilities and expected losses is fundamental for the success of any risk management strategy (Kunreuther, 2003).

Both the Hyogo and the Sendai Frameworks have underlined the importance of risk understanding and, in turn, of data collection and risk assessment. Since then, substantial progress was made, but, nevertheless, major gaps still affect many countries (UNISDR, 2017). In particular, UNDRR (2019) identifies four challenges about data on risks: availability, quality, accessibility and application. Availability concerns data collection, a necessary step for risk assessment. Understanding natural risks requires an enormous amount of information that are costly to collect and, in addition, natural disasters are rare events and therefore creating a database requires time, at least decades. Along with long times of observation, high-quality data is necessary to guarantee effective analysis. Insurers and reinsurers are among the major data producers in the world in terms of both dimensions and quality of their databases, but they are

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[10] When assessing natural risk a variety of impacts should be considered on different groups across the society. Impacts might be direct or indirect, as shown by World Bank (2014) for the government, homeowners, farmers and the poorest.

[11] As argued by Field et al. (2012), use and applicability of cost-benefit analysis to risk reduction measures are constrained by important limitations, that Mechler (2016) summarizes in: (i) representing disaster risk, (ii) assessing intangibles and indirect benefits, (iii) assessing portfolios of systemic interventions versus single interventions, (iv) the role of spatial and temporal scales. Despite these limitations, the author argues that cost–benefit analysis remains an important tool for prioritizing efficient disaster risk measures and is well suited for the evaluation of infrastructure-based options. By contrast, preparedness and systemic interventions can be better evaluated by means of other tools such as cost-effectiveness analysis, multi-criteria analysis and robust decision-making approaches.

usually not keen to share their database. Data accessibility strongly limits the analysis of natural riskiness and is not confined to private entities as several countries show difficulties in data-sharing among government institutions. However, accessing to a high-quality database is not sufficient for accurate analysis: data should in fact fit the purpose of the study.

Data analysis is by far more problematic than data collection. As risk is determined by a combination of hazard, exposure and vulnerability, any change in the society, landscapes, or technology might completely reshape the area's risk profile. As a consequence, past events might no more be representative of the area and this challenges the possibility of projecting the future from the past, or at the least, that classical statistical techniques can be used. To overcome these problems, a new approach to risk assessment, called "catastrophe-modeling", has been developed.[12] Catastrophe models are software that combine geological, engineering, IT and statistical knowledge to simulate the effects of natural events on the territory.[13] These sophisticated tools are widely adopted by the insurance industry and are increasingly used by governments also.[14] These software require continuous updating and their developers are constantly striving to achieve ever more accurate predictions of losses. To date, there are models capable of describing almost all natural risks, but some important eventualities are not yet satisfactorily represented,

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[12] Catastrophe-modelling began in the 1960s, but its adoption is much more recent. The first commercially produced model dates back to twenty years later. When introduced, their use was not widespread. They became increasingly popular in the insurance industry from 1989, when Hurricane Hugo and the Loma Prieta Earthquake caused severe losses to US insurers, and then Hurricane Andrew in 1992, that led nine insurers to insolvency, furthermore incentivized their adoption (Grossi, Kunreuther, and Windeler, 2005). Since the early beginning, insurance industry has been the most important driver of their development. From the 2000s developers have started including insurance pricing in the models, and actuarial standards and guidelines for the use of catastrophe modelling have been published by the actuarial society of both Europe and the US (Mitchell-Wallace et al., 2017).

[13] Note that, despite these models simulate the impacts of natural disasters to overcome lack of data, historical records are still necessary and serve as input for the simulation process.

[14] The first country in investing in catastrophe-modelling was the US. In 1997 FEMA produced HAZUS, a catastrophe-model to estimate earthquake losses in the Country. The model has later been extended to floods and hurricanes. More recently, around the 2010's, there has been a large-scale revision of the existing catastrophe-models and new ones emerged. Some of these have been produced by governmental organizations, like for example, R-FONDEN in 2007, created through a partnership between the Mexican Natural Disasters Fund (FONDEN) and the Ministry of Finance with the technical support of the Institute of Engineering of the UNAM (Universidad Nacional Autónoma de México) (World Bank, 2012a).

including cascading effects, multi-hazard analysis, spatial correlation between assets exposed (Mitchell-Wallace et al., 2017). Furthermore, these models are tied to the characteristics of the areas on which they are built and might not represent regions that are too different from the reference area.

2.3.2 Governance

Currently most countries are addressing the consequences of disasters rather than trying to reduce their actual risk (Opitz-Stapleton et al., 2019; UNDRR, 2019). This purely "corrective" attitude[15] is the main weakness of disaster risk management strategies, which should instead define a plan of interventions aimed at building the skills necessary for the community to face adverse events or to limit them. However, developing "progressive" disaster risk management is much more complex than just dealing with consequences. First of all, managers should move from a single-threat to a multi-threat perspective, recognize the existence of multiple sources of risk, potentially correlated, and prepare to face all of them (UNDRR, 2019). Secondly, the manager must prepare a plan of interventions that should be effective in the long run. For example, in the case of risk mitigation interventions, this means not only to fund the initial investment, but also to provide for all maintenance activities that will guarantee its future functioning. Finally, it is essential that the risk management strategy is included into a broader management plan, so that consistency between the actions of the various governmental offices will be guaranteed. For example, it urban development plans should not provide for settlements expansion in high-risk areas (Rozenberg and Fay, 2019).

This approach is much broader and much more expensive in terms of both time and cost than simply fixing the consequences. In addition to the difficulty of planning, other factors negatively influence managers' choices. Studies on the relationship between natural disasters and election suggest that it may not be convenient for a government to invest in disaster reduction. In fact, if on the one hand the population tends to blame the government for natural disasters (Achen and Bartels, 2004), on the other hand politicians are discouraged to invest in risk mit-

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[15] According to Twigg (2015), corrective risk management are project-oriented strategies composed by measures that address specific current risks only. As opposed to the corrective strategy, the progressive disaster risk management is process-oriented and builds a range of capacities to cope with future threats, both anticipated and unforeseen.

igation because electorate has short memory and benefits from the intervention may take years and may even appear once the ruling party has changed (Cavallo and Noy, 2009). In addition, Healy and Malhotra (2009) found evidence that voters reward presidential party for disaster relief but not for investing in disaster preparedness. This might explain why governments appear so generous in spending on disaster relief during the election (Cole, Healy, and Werker, 2012). Along with political pressure, decision-makers might fail to recognize the importance of hazards and vulnerability to national development, might be excessively risk-prone or reluctant to allocate substantial resources for events that might not even happen (Michel-Kerjan and Slovic, 2010; Opitz-Stapleton et al., 2019).

2.4 Toward a community-based risk management approach

As countries slowly revise their plans, risk evolves quickly: the sheer number of people on Earth, climate change and the dynamic connectedness of biological and physical worlds are making natural risks increasingly systemic. Since risk is the result of individuals and collective decisions, the United Nations warn that, as risk gets more and more complex, responsibilities cannot be clearly assigned to the different stakeholders. Governments are able to influence risk-generating or risk-reducing behavior in the population, in the private, public and voluntary sectors through public policies, hence UNDRR (2019) argues that *"by incentivizing transdisciplinary, integrated, multisectoral research engaging non-traditional counterparts, risk assessment and decision-making efficiency can be improved, duplication of effort reduced, and connected collective action facilitated. National planning bodies with representation from all sectors must develop risk reduction strategies that assume an "all-of-State" institutions approach to risk reduction"*.

The United Nations encourage countries to establish solid partnerships both with private stakeholders and between governments, but, though necessary, they can also be difficult to manage. In particular, a United Nations survey on public-private partnerships for natural risk management UNISDR (2008) revealed that an active participation of all the community at risk is fundamental for the effectiveness of a strategy, but it can be achieved only if the government is able to create the proper conditions. First of all, arousing the interest of the private sector is necessary, as firms will participate in the initiatives only if they deem them convenient, and maintain their commitment over time. Since a plurality of private subjects make up the community, disaster risk management should be mutually beneficial and local authorities must encourage active and productive dialogue among the subjects involved (for example, between insurance and academia). In order to involve private companies, the government can ask them to develop a project and make them responsible for the parts that compete with them. Furthermore, the role of individual citizens, who can make an important contribution if properly informed and involved, should not be overlooked. In fact, educating the right segment of the population can encourage risk reduction behaviors, and fosters the dialogue between individuals and authorities. It is also important that citizens believe in the risk management strategy, so that they will actively engage in safety and involve more and more people. Trust between institutions and partners is essential for the success of the strategy and it is the duty of the government to constantly nourish it (for example by punishing the fraudulent companies that offer individuals risk reduction goods or services at excessively high prices), but constant monitoring private partners is also crucial.

A "community-based disaster risk management"[16] raises the voice of people that are hence able to better communicate vulnerabilities to the governor, thus allowing for a more comprehensive view of risk. Understanding the social context is in fact essential for the construction of effective measures, and it is particularly important to reach out the weakest segments of the population.[17] In particular, Twigg (2015) claims that "*participatory risk reduction initiatives are more sustainable because they build*

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[16] World Health Organization (2015) defines a community as "*a group of people living in the same environment, sharing the same livelihood. [...]. Community members are the immediate victims of the adverse effects of disasters and they have the best knowledge about their local surroundings such as demographic, social, economic, and cultural status, risky areas, water sources, roads and health facilities. In addition, community members have information about the vulnerable groups [...] and can assist health care*". Community-based disaster risk management empowers the community, address the root causes of risks and address it through local knowledge and expertise and for this reason activities and actions vary from one community to another (Heijmans, 2009).

[17] Some studies have shown that the poorests are more vulnerable to natural disasters due to their limited ability to cope with disasters (Hallegatte, Vogt-Schilb, et al., 2017). As the impact of natural disaster on well-being might also be tremendous, other factors impacting vulnerability are inequalities concerning gender, age, education, ethnicity, wealth, health status, disability, access to resources and environmental concerns (Hallegatte, Rentschler, and Walsh, 2018; Shukla et al., 2019).

on local capacity, ideas can be tested and refined before adoption, and they are more likely to be compatible with long-term development plans. They may also be more cost-effective in the long term than externally-driven initiatives". Unfortunately, in Twigg (2011), the author argues that reality diverges from the desirable scenario of trust, collaboration and dialogue.

In addition, developing countries could enormously benefit from collaborations between national governments and international institutions such as the World Bank, which for their part are interested in promoting risk reduction to contain future expenses (Kunreuther, 2003). Most regions with high exposure to natural hazards are involved in projects with intergovernmental organizations coordinating the disaster risk management (UNDRR, 2019), though some advancement is still needed. On the negative side, sometimes a lack of trust has hindered collaborative preparedness effort in conjunction with international aid agencies (Twigg, 2015), and collaboration between national governments should be strengthened.

2.5 Final remarks and future challenghes

In 2015, the United Nations declared that natural hazards could erase decades of progress (United Nations General Assembly, 2015), but development itself fosters natural hazards. In fact, unsustainable development leads to an increase in social inequalities and in the number of poor who, because of their limited resources, constitute the most vulnerable and least resilient segment of the population. In turn, inequalities create social and political exclusion, and since the participation of the whole community is necessary for risk understanding, this poses a further obstacle to the effectiveness of the managers' choices (UNDRR, 2019).

Especially in the poorest countries, development went along with rapid urbanization, which has strong impacts on risks. Cities are in fact extremely dangerous due to biological, chemical, physical, and sociopolitical conditions. In addition, they host large numbers of low-income people who live in low-quality facilities, sometimes without access to adequate infrastructure. The urbanization process, often carried out in an uncontrolled way, has therefore brought together a large number of extremely vulnerable people in highly risky areas (Dickson et al., 2012). In this respect, Hallegatte, Vogt-Schilb, et al. (2017) registered a global trend toward increased risk taking: *"from 1970 to 2010 the world population grew by 87 percent, while the population in flood plains increased by 114 percent and* *in cyclone-prone coastlines by 192 percent"*. The situation aggravates when appropriate building codes are lacking.

Further consequences of urbanization are damage to the ecosystem and deforestation, which can cause the emergence of new natural phenomena, such as the spread of new diseases (Opitz-Stapleton et al., 2019). Climate change runs faster every year and its consequences are more and more tangible all over the world. According to Geneva Association (2013) and Geneva Association (2018), the changing climate is challenging the weather-relater branches of the insurance industry. State-owned insurance and reinsurance companies are particularly fragile since, being bound by subsidy rules and government choices, are less flexible than private ones and will not be able to adapt their prices quickly (Penning-Rowsell, 2015; Olcina et al., 2016; Oldenborgh et al., 2017). According to Hallegatte, Bangalore, et al. (2016), climate change could drag up to 100 million people into poverty by 2030, but the financing needs for adaptation in developing countries far exceed funds available (World Bank, 2010). Country's reluctance in investing in adaptation is largely due to the uncertainty surrounding the projects' benefits and, in addition, government undertaking some project may not be well-rewarded by the population, whose support or opposition is determined by the perception of danger associated to climate change or to the use of current technologies (Kunreuther, Gupta, et al., 2014). A first step that governments can take toward building a more climate-resilient society is encouraging or forcing private initiatives through adequate spatial planning frameworks, infrastructure projects and policy appraisals, regulatory and economic standards (OECD, 2018a). Public-private partnerships can channel and coordinate the efforts and objectives of governments and multiple private entities - project companies, lenders, shareholders, insurers and professional advisors - provided that tasks and responsibilities are clearly assigned (World Bank, 2016). In order for the plan to be effective, governments should ensure consistency with the other policies adopted which could otherwise distort the climate-resilient incentives and discourage the adoption of the desired solutions (OECD, 2018a). As argued by the Hallegatte, Bangalore, et al. (2016), we hence need to rapidly switch to inclusive climate-informed development.

In light of this, it is increasingly evident that the management of natural risks cannot be effectively achieved unless included in a sustainable development plan. UNDRR (2019) warns that *"with increasing complexity and interaction of human, economic and political systems within ecological systems, risk becomes increasingly systemic. [...]. The way in which such changes –*

including in the intensity and frequency of hazards – affect human activity is yet difficult to foresee. Current approaches to risk measurement and management are inadequate to meet the challenges of the multifaceted interconnectedness of hazard, the barely understood breadth of exposure, and the profound detail of vulnerability".

A "development-enhancing risk-management" includes risk reduction in the development plans, allowing to define a set of coherent actions and thus avoiding those conflicts of interest that have led to a scarce commitment of local authorities in risk mitigation. Furthermore, it takes into account all the externalities of a risk reduction measure, some of which may not concern natural risks (Clarke and Doherty, 2004; Kunreuther, 2006b; OECD, 2018a). A first step in embracing this comprehensive approach might be incorporating risk reduction measures into existing funding streams (Twigg, 2015), for example by activating a coupled loan and voucher program for homeowners to relocate out of risk-prone areas (Kousky and Kunreuther, 2014). governments might also prevent risk creation and foster mitigation by setting appropriate development-related standards and regulations, policies on social protection and payment for ecosystem services.

Although it is recognized that a large part of the capital for risk mitigation works cannot but come from the public sector (Paudel, 2012), even large companies have the financial capacity to bear the costs of some infrastructural interventions. A public-private partnership can encourage investments by financially strong private stakeholders. For example, a government that enters into an agreement with local insurance companies by offering adequate guarantees for the highest levels of loss without completely relieving them of the risk assumed, can create the ideal conditions for the insurance companies to invest in structural works that further lower the local level of risk. In this sense, a partnership between the government and several insurers, can facilitate agreement between the insurers to co-financing these works, so that the cost for each company is lowered while benefits are kept constant. In addition, governments that provide a facilitated guarantee to insurance companies can request a fee, which can be re-invested in risk mitigation, thus slightly lowering the pressure on public accounts and the need for public ad-hoc post-disaster relief.

In order for the investment in risk mitigation to be profitable in terms of cost-benefits for an insurance Company, it is essential that the insurer has a solid and broad policyholder base (Hudson, Ruiter, et al., 2020; Paudel, 2012). The government can therefore encourage its construction by introducing a strict mandatory requirement, for example by requiring the coverage for natural disasters be included in the general basic policy. In addition, a good incentive for citizens to buy policies can be provided by banks, which often require those who take out mortgages to insure the property purchased.

In addition to large public or private investments for the community, strengthening interventions on private homes are also advisable and, overall, can have an important effect in reducing the impacts of natural disasters. To this end, evidence was gathered that risk-based premiums with discounts for risk mitigation can stimulate private initiative (Surminski and Hudson, 2017). In order for these premiums to remain affordable even in the most at-risk locations and for the less wealthy citizens, the government can provide special vouchers to these categories.

A further advantage of a public-private partnership with a high number of stakeholders is that a nationally representative body can coordinate the actions of all, avoiding development choices by local authorities as well as risk fostering actions that conflict with risk management objectives. Furthermore, this body can verify that all types of natural hazards are addressed and that development choices take into account the needs of all stakeholders and are always aimed at maximizing collective wellbeing. The increased involvement of the community can help the coordinating authority in identifying the critical issues to be managed and the factors to be considered in management choices thanks to a better and more inclusive risk assessment.

Investments in risk mitigation are essential for the partnership to be sustainable for the public sector, whose resources often run out quickly due to recovery. However, risk mitigation is not sufficient and a large contribution to the stability of the system should come from a number of financial instruments. Among these, traditional reinsurance, ILS, or state-contingent debt instruments can help dealing with the post-disaster phase, while green bonds can foster climate change adaptation (Opitz-Stapleton et al., 2019). The high complexity of these tools has often constituted an important barrier to their adoption but, thanks to a partnership with insurance and financial institutions, the government would be able to receive adequate technical support during both their construction and management.

Table 1: State-owned insurance companies (examples).

Country, Name, Year	Peril	Position in the Market	Policy Details	Risk Reduction
California, California Earthquake Authority[1], 1996	Earthquakes	Co-insurance with private insurers.	California insurers are obliged to offer earthquake policies, but they can choose whether to co-operate with CEA or not. Policy purchase is voluntary. Risk-based premium. Possibility to choose deductibles and maximum coverage.	Incentives for risk mitigation (discounted premiums), Reinsurance.
Iceland, National Catastrophe Insurance of Iceland[2], 1975	Avalanches Earthquakes Floods Landslides Volcanic eruptions	Private insurers collect and transfer premiums, and receive a commission.	All buildings and contents insured against fire are also insured against catastrophe risks. Fire insurance is compulsory. Flat premium set by law. 5% Minimum deductible.	Reinsurance, If the agency borrows funds, such loans are unconditionally guaranteed by the government.
New Zealand, Earthquake Commission (EQC)[3], 1993	Earthquakes Floods Hydrotermal activity Natural landslides Tsunamis Volcanic eruptions	Co-insurance with private insurers.	Specific building cathegory are covered compulsorily and automatically along with fire insurance. If the building is not insured for fire, is also not covered for natural risks. Flat rates. Applies fixed maxima and deductibles.	Reinsurance, Unlimited State guarantee.
Spain, Consorcio de Compensacion de Seguros[4], 1954	Atypical cyclonic storms Earthquakes Extraordinary floods Fall of meteorites Tsunamis Volcanic eruptions	Private insurers collect and transfer premiums, and receive a commission.	Compulsorily included in personal accident policies, life insurance and some branches of property damage. Flat rates. Deductibles apply to most for the covers.	Unlimited State guarantee.

Continued on next page

Table 1 – continued from previous page

Country, Name, Year	Peril	Position in the Market	Policy Details	Risk Reduction
Taiwan, Taiwan Residential Earthquake Insurance Fund[5], 2001	Earthquakes	Co-insurance with private insurers	Compulsorily attached to all residential fire insurance policies. Flat rates. Applies maxima.	Reinsurance, State guarantee.
Turkey, Turkish Catastrophe Insurance Pool[6], 2000	Earthquakes	Accredited insurance companies and agents arrange policies on behalf of the TCIP.	Compulsory for certain types of buildings and dwellings. Partially risk based rates (5 risk zone, 3 construction types). Applies maxima.	Reinsurance, Contingent Credit Line.
U.S., National Flood Insurance Program[7], 1968	Floods	Competes with private insurers.	Residential buildings and contents policies are offered to those communities that participate to the program. Communities' can participate to the program but are not forced. If they do, they undertake to adopt appropriate preventive measures. Members of a community involved are not forced to buy policies. Risk-based rates. Applies maxima and deductibles.	Incetives for risk mitigation, Government as lender of last resort.

Continued on next page

Table 1 – continued from previous page

Country, Name, Year	Peril	Position in the Market	Policy Details	Risk Reduction

[1] California Earthquake Authority, Audited Financial Statements 2018.

[2] Government of Iceland, ACT 55/1992 on The Natural Catastrophe Insurance of Iceland after changes to NTI‘s legislation in July 2018.

[3] New Zealand Government, “Earthquake Commission Act 1993”; Civil Defence – New Zealand, “Government Financial Support”, 2009.

[4] Consorcio de Compensación de Seguros (2008), Consorcio de Compensación de Seguros (2017), and Machetti (2004).

[5] Government of Taiwan, “Insurance Act”, art 138-1, 1999; Government of Taiwan, “Enforcement Rules for Coinsurance and Risk Assumption Mechanism of Residential Earthquake Insurance”, 2001; Government of Taiwan, “Taiwan Residential Earthquake Insurance Fund Articles of Incorporation”, 2001; Government of Taiwan, “Regulations Governing Taiwan Residential Earthquake Insurance Fund”, 2001; Government of Taiwan, “Enforcement Rules for the Risk Spreading Mechanism of Residential Earthquake Insurance”, 2008; Taiwan Residential Earthquake Insurance Fund (TREIF), Annual Report 2015.

[6] Yazici (2006), World Bank (2011), and Gurenko et al. (2006); Turkish Government, Law no: 4452 “Measures to be taken Against Natural Disasters and Authorization in Regards to Arrangements to be made in Overcoming the Damage Caused by Natural Disasters”, 27/08/1999; Turkish Government, Decree Law no: 587 “Decree Law Relating to Compulsory Earthquake Insurance”, 27/12/1999; Turkish Government, Law no: 6305 “Catastrophe Insurance Law”, accepted 09/05/2012; Turkish Government, Tariff and instruction of compulsory earthquake insurance, Official Gazette 28512, 29 December 2012.

[7] All-Hazard Authorities of the Federal Emergency Management Agency, “The National Flood Insurance Act of 1968” as amended 42 U.S.C 4001 et seq., sec 1366, Office of the General Counsel, August 1997; US Government, “Disaster Mitigation Act of 2000”, Public Law 106-390,30 October 2000; Federal Insurance and Mitigation Administration - FEMA, “FY 2016 Pre-Disaster Mitigation (PDM) Grant Program. Fact Sheet”, FEMA, 2016; United States Code, Title 42. The Public Health and Welfare, Chapter 68. Disaster Relief, “Robert T. Stafford Disaster Relief and Emergency Assistance Act”, Public Law 93-288, signed into law 23 November 1988, last amended April 2013.

Table 2: State-owned reinsurance companies (examples).

Country, Name, Year	Peril	Policy Details	Reinsurance Contract	Risk Reduction
Florida, Florida Hurricane Catastrophe Fund, 1993	Hurricane	Property insurance policies must include coverage for hurricane. Policyholders are eligible for premium discounts for installing certain wind resistant features on their homes. Hurricane policies may include a deductible.	Insurers are obliged to cede residential property's hurricane risks to the fund. Insurers select a coverage percentage of 45%, 75%, or 90%. A participating insurer's premium, retention, and coverage limit are based on its total insured values by ZIP code.	Retrocession. ILS. +Post-event bonds.
France, Caisse Centrale de Réassurance, 1946 (natural risks cover from 1982).	Natural events that the government declares disasters, except storms, hail, snow, frost.	Natural disaster coverage is compulsory in all property insurance policies. Rates are set as percentages of the premium of the basic insurance policy.	The company offers unlimited cover for specific classes of business in the French market. Insurers decide whether to cede risks to CCR or not.	Guarantee of the French State. Risk Prevention Plans.
Japan, Japanese Earthquake Reinsurance Co., 1966	Earthquakes. Volcanic eruption.	Earthquake insurance are compulsorily written with fire policies on residential dwellings and/or personal properties. The amount insured is 30-50% of the amount provided by the fire policy, but is limited to a fixed maximum. The premium is risk based and set by law. Discounts for earthquake-resistant buildings are available.	JER compensates 100% of the claim that the insurer paid to the policyholder. Reserves are made up of policyholders' premiums, capital by the government, investment profits from these accumulated liability reserves. If an event occurs, each of JER, non-life insurers and the government pays a claim according to each liability.	JER and non-life insurers pay claims up to 87.1 billion yen per earthquake. The non-life insurers, the government and JER share equally claims for the portion exceeding 87.1 up to 153.7 billion yen. The government pays a majority of claims for the portion exceeding 153.7 billion yen. JER also buys retrocession.

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Table 2 – continued from previous page

Country, Name, Year	Peril	Policy Details	Reinsurance Contract	Risk Reduction
UK Flood Re 2016	Flood	Insures decide whether to offer a policy or not and set the price.	Flood Re compensates 100% of the claim that the insurer paid to the policyholder. Any insurer that offers home insurance in the UK must pay a levy to Flood Re. Insurers can choose to pass the flood risk to Flood Re for a fixed price.	Government's commitment to risk mitigation. Flood Re buys its own reinsurance programme every three years to cover losses of up to £2.2bn per annum.

[1] Florida Hurricane Catastrophe Fund, Annual Report of Aggregate Net Probable Maximum Losses, Financing Options, and Potential Assessments, February 2020.

[2] Caisse Centrale de Réassurance, Activity Report 2018.

[3] Japan Earthquake Reinsurance, Annual Report 2019, Introduction to Earthquake Reinsurance in Japan.

[4] Flood Re, Annual Report and Financial Statements, Year ended 31 March 2019.

Chapter 3

Assessing the risk of earthquakes and floods in Italy

This Chapter is a joint work with my supervisors Giorgio Stefano Gnecco and Fabio Pammolli. The full text of the article is also available from the arXiv repository, preprint number 2006.05840.

Abstract

According to the traditional statistical techniques, expected losses can be extrapolated from the analysis of the historical records of past losses. Natural hazards, however, with their long times to return rarely offer large databases to analyze. To compensate for the lack of data, risk analysts thus began to reconstruct the natural risk from soil or atmospheric data, land registry and information on the vulnerability of the structures exposed. Referring to the latter branch of research, we propose here an analysis of seismic and alluvial risks for the Italian residential building stock.

3.1 Introduction

Expected losses are traditionally estimated from records of past events, but when data are too scarce or not available, alternative techniques are needed. During the last decades, a new family of models inferring losses from the characteristics of soil and structures has emerged (Grossi, Kunreuther, and Windeler, 2005). According to this branch of literature, risk can be reconstructed as a combination of four components:

- Hazard (H) provides a phenomenon description based on physical measurements, usually frequency, severity, and location.
- Exposure (E) identifies the object at risk.
- Vulnerability (V) defines the relationship between hazard and exposure, quantifying the impact of the catastrophic event on the property under analysis.
- Loss (L) converts physical damages into monetary values.

Each component is defined on a series of geophysical, engineering or financial variables and relations, and equally contribute to the overall estimate of risk (Mitchell-Wallace et al., 2017). Through a proper definition and combination of these components, a risk model should describe the geological or environmental features of the peril in analysis and should also capture differences in impacts on the relevant structural typologies.

Although this line of research is growing fast, not many models are currently available and not any peril has been satisfactorily described. Moreover, these models, while not requiring data on losses, need a large amount of information on soil, weather, and housing. In addition to the difficulty of finding this data, models strongly depend on geographical and urban features of the area they have been defined on, and therefore can hardly be adapted to other territories (Hufschmidt and Glade, 2010; Scorzini and Frank, 2015). We propose new techniques for measuring risk when historical data lack.

As far as Italy concerns, current literature offers some analysis that allow to appreciate seismic risk on the whole territory, while little is still known about floods. We therefore refer to the existing literature for seismic risk and propose a more detailed representation of the probability of earthquakes occurring. Our methodology is similar to Cesari and D’

Aurizio (2019). A new model is developed for flood assessment in order to compensate for the lack of knowledge about floods in Italy as well as the scarcity of historical data and information on the basins. Although better accuracy of the estimates is desirable for the future, our models provide a quantification of losses at the individual and local level that can support the authorities in risk management. For example, they can set the basis for the construction of a public insurance system.

After a brief presentation of the database, the following two sections present earthquake and flood risk assessment respectively. Although the two model strongly differ, they both combine the four risk components as:

$$\text{Expected monetary damage} = L \times E \times \int V(H)\mathrm{d}(H). \tag{3.1}$$

After a general description of the model, each of these sections discuss the components separately. The following section presents results and then this chapter concludes with a discussion of our model's uncertainty. Our analysis considers residential housing only, furniture not included. Multi-hazard risk assessment is postponed to Chapter 5.

3.2 Data

There is currently no database collecting records on impacts from natural disasters in Italy, but some information on national riskiness is available, thought data quality is sometimes questionable. In particular, our models require data about hazard and exposure.

Hazard

While seismic hazard is well documented, flood data are strongly affected by the lack of a single body responsible for physical detection.

Seismic movements are in fact regularly monitored by the National Institute of Geophysics and Volcanology (INGV), that freely provides daily updated databases both on past events and about several seismic indicators. Records are georeferenced and cover almost all the national territory, indicators are presented for different probability scenarios and associated to an accuracy index. Data for the analysis of earthquake has been drawn from INGV's maps of seismic riskiness. On the other side, flood monitoring is demanded to a number of regional authorities -

named “basins’ authorities” - that independently choose collection methods and indicators. These differences in data collection often leads to inconsistencies and poor comparability among regions (Molinari, Aronica, et al., 2012). The main database on hydrological risk in Italy is the AVI (“Aree Vulnerate Italiane” - “Italian Vulnerable Areas”) archive managed by National Research Council (Guzzetti and Tonelli, 2004). The archive collects historical information on flood events in Italy (mainly from 1900 to 2002). However, records are mostly gathered from local journals and, unfortunately, are rarely suitable to scientific analysis: information are provided in a narrative form, georeferencing is poor, physical phenomena description is not uniform and data quality depends on the original source (Molinari, Menoni, et al., 2014). Despite these limitations, the archive is currently among the best representation of the flood hazard and has therefore been used here. Information from the archive have been integrated with data from “Italian Flood Risk Maps” (EU Directive 2007/60/CE) indicating the perimeter of geographic areas that could be affected by floods according to three probability scenarios (Decreto Legislativo 23 Febbraio 2010 n.49, 2010): extreme events with time to return 500 years (P1); events with time to return of 100-200 years (P2); events with time to return between 20-50 years (P3).

Exposure

As far as exposure concerns, we refer to the “Mappa dei Rischi dei Comuni Italiani” (“Riskiness Map of Italian Municipalities” - MRCI). This database has been created during a recent institutional project - “Casa Italia” - to the aim of providing the best representation of major natural risks in Italy (volcanic, seismic, hydrological, geological). Among several risk indicators, the database presents a fairly rich representation of Italian real estate. Additional information on regional average house’s squared meters and the average dwelling value are estimates by the Revenue Agency (Agenzia delle Entrate, 2015).

3.3 Earthquake

Earthquakes and land movements are among the most studied risks in the literature, but most of the analysis focus on vulnerability and explore the relationship that links hazard intensity and damage to buildings. As far as Italy concerns, a few analysis investigate the number of deaths, missing persons and/or injured people (Cascini, Ferlisi, and Vitolo, 2008; Salvati et al., 2010; Marzocchi et al., 2012), while, to our knowledge, risk assessment on residential risk is presented in Asprone et al. (2013) only. The latter model follows the structure specified in eq. (3.1) and has been tested on the L'Aquila earthquake, therefore we are referring to it for seismic loss estimates. Some slight modification of the model has been introduced in order to update the analysis with latest released data on hazard and to consider a wider range of potential loss scenario. Moreover, our real-estate database provides a more detailed representation of residential housing, thus allowing for higher accuracy of the estimates.

Damages have been estimated per municipality relating the peak ground acceleration (PGA) and its exceedance probability $\lambda(PGA)$ with the existing residential building stock by means of fragility curves. Given a certain set of "limit states" (LS) representing subsequent level of damage (usually from "no damage" to "collapse"), a fragility curve describes the probability of reaching a given limit state as a consequence of the observed PGA, $P\left(LS|PGA\right)$. Expected loss can be estimated by comparing fragility curves of each LS. Damages are then monetarily quantified by means of a function $RC(LS)$ linking the property's value to the level of damage.

Literature offers many fragility curves' models, and we rely on Asprone et al. (2013) selection for Italy (Table 4). Each model k applies to a number of specific building structures and is defined on N_{LS_k} limit states chosen by the authors to describe the impact of earthquakes on the j-th structure. Since many models may address the same j-th structure, losses are estimated by averaging results from the K_j models describing j.

Municipal residential housing stock is divided into five relevant structural typologies - thus fixing $j = 1, \ldots, 5$ - and seismic losses per square metre l^s are computed for each j and each municipality c.

Given the probability $P_k\left(LS+1|PGA\right)$ of the structural typology j of suffering a damage level LS given a certain PGA, expected losses are estimated as:

$$
\begin{aligned}
l^s_{j,c} = \frac{1}{K_j}\sum_{k=1}^{K_j}\sum_{LS=1}^{N_{LS_k}} RC(LS) \int_0^\infty \left[P_k\left(LS|PGA\right) - P_k\left(LS+1|PGA\right)\right] \\
\mathrm{d}F_c\left(PGA\right) = \\
= \frac{1}{K_j}\sum_{k=1}^{K_j}\sum_{LS=1}^{N_{LS_k}} RC(LS) \cdot \int_0^\infty \left[P_k\left(LS|PGA\right) - P_k\left(LS+1|PGA\right)\right] \\
\left|\frac{\mathrm{d}\lambda_c\left(PGA\right)}{\mathrm{d}(PGA)}\right| \mathrm{d}(PGA).
\end{aligned}
\tag{3.2}
$$

where $F_c(PGA) = 1 - \lambda_c(PGA)$ is the cumulative density function of PGA for the c-th municipality. According to Asprone et al. (2013), we assume $P_k\left(N_{LS_k}+1|PGA\right) = 0$. Model (3.2) combines a probability distribution with domain $[0,\infty)$ and a damage function increasing with PGA. PGA is traditionally expressed in gravity acceleration units g and Asprone et al. (2013) bounds the integration variable PGA to $[0, 2g]$. Since we wanted to include as many scenarios as possible, we extended the domain to include even most unlikely events, and therefore the considered domain is $[0,\infty)$.

The five municipal losses estimates have been multiplied by municipal exposure and then aggregated into municipal total seismic losses L^s_c.

$$
L^s_c = \sum_{j=1}^{5} l^s_{j,c} \cdot E^s_{j,c}. \tag{3.3}
$$

3.3.1 Hazard

Seismic hazard is represented by PGA and its annual probability of exceedance, which are both available on the INGV website (Gruppo di Lavoro MPS, 2004) for most of Italy[1].

INGV released seismic maps for 9 probabilities of exceedance in 50 years (Meletti and Montaldo, 2007). Those PGA measurements are presented for points in a 0.05-degree grid drawn on the Italian map. Grid

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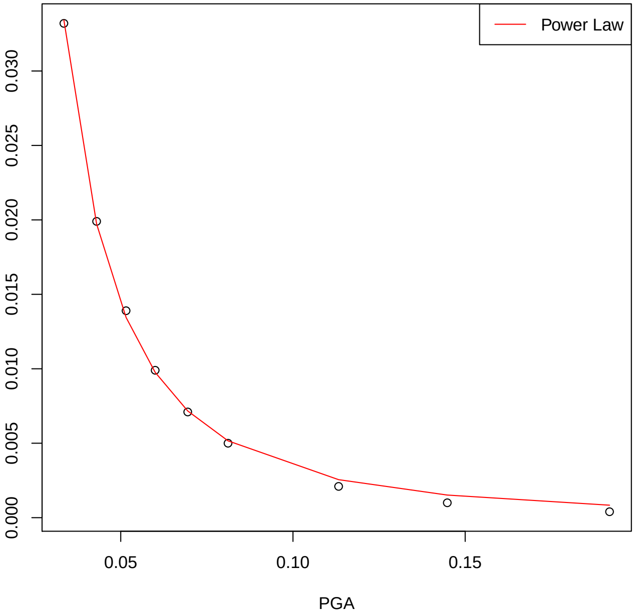
[1] Sardinia, Alicudi, Filicudi, Panarea, Pantelleria, Pelagie Islands, Stromboli, Ustica not included.

Figure 1: PGA exceedance probability.



Note: the plot shows the PGA distribution of a random municipality. The nine points are data by INGV, and the red line represent fitting with the power law distribution.

points are defined by longitude and latitude and can be associated to a municipality by means of reverse geocoding, that led to the definition of a PGA distribution for over 4600 municipalities. Sometimes more points referred to the same municipality, hence their average value has been considered. In order to capture the widest possible representation of the territory, missing municipalities have then been approximated by averaging the neighbors' PGA values. However, we failed to represent the whole national territory since Sardinia and many other small islands cannot be captured by neighborhood (missing municipalities can be seen in Figure 7). Our database is thus composed of 7685 municipalities.

The 9 INGV measurements describe the tail of $\lambda(PGA)$ for each grid point (a grid point's PGA curve example is plotted in Figure 1). Asprone et al. (2013) assumed uniform seismicity in each municipality, but the known curve's sections in Figure 1 do not seem to reflect this hypothesis. Moreover, since the left-side of the curve is missing, classical fitting methodologies led to unsatisfactory results, often overestimating tails. Therefore, parameters of the distribution have been estimated by regression. Best fitting results have been obtained by the power law distribution.

In order for the hazard curves to reflect the soil category at the building foundation, O.P.C.M. 3274 (2003) and Decreto Ministeriale 14/01 (2008) state that PGA values at the bedrock should be multiplied by the stratigraphic S_S and topographic S_T amplification factors. These factors have been computed by Colombi et al. (2010) for all the Italian municipalities and kindly provided by INGV.

Table 3: Number of buildings per seismic structural typology.

	Material	Building Code	Buildings (u=1000)
RC gl	Reinforced concrete	Gravity Load	2853.96
RC sl	Reinforced concrete	Seismic Load	636.92
M	Masonry	Gravity Load	6975.98
A gl	Other Structures	Gravity Load	1406.21
A sl	Other Structures	Seismic Load	260.88

3.3.2 Exposure

As seismic events differently affect buildings, relevant structural typologies have been identified based on the information available.

First, the MRCI database divides municipal housing stock into: masonry, reinforced concrete, and other; Asprone et al. (2013) argue that buildings of type "other" contain both components of reinforced concrete and masonry structures, so we assumed this category to be a mixture of these two.

These structures may then have been built in compliance with modern anti-seismic requirements or not. Since the database does not include this information, we refer to the construction year and building laws in force. In fact, from 1974 a series of subsequent laws (Legge n. 64, 2 feb, 1974) led to the progressive re-classification of risk-prone areas, where more restrictive anti-seismic construction requirements entered into force, thus substantially modifying buildings' structures. The process ended in 2003 when anti-seismic laws (O.P.C.M. 3274, 2003) were extended to the whole Italian territory. Thus, we define reinforced concrete and other structures as seismic loaded if built after these laws entered into force, or gravity loaded otherwise[2]. According to Asprone et al. (2013), we assumed masonry as seismic loaded only. Therefore, we refer to 5 structural typologies (see Table 3) : masonry (M), and gravity or seismic loaded reinforced concrete ($RC.gl$ and $RC.sl$), gravity or seismic loaded other-type structures ($A.gl$ and $A.sl$).

Since $l^s_{j,c}$ is the expected seismic loss of the structure type j in the municipality c per square metres, $E^s_{j,c}$ is obtained by multiplying the number of buildings $B_{j,c}$ by the average apartment's surface $\bar{s}_c$ (Agenzia delle Entrate, 2015) and the average number of apartments per building $\bar{A}_c$ (ISTAT, census 2015):

$$E^s_{j,c} = \bar{s}_c \cdot B_{j,c} \cdot \bar{A}_c. \tag{3.4}$$

3.3.3 Vulnerability

Seismic vulnerability is represented by fragility curves, that provide the probability of exceeding a certain damage state, given some hazard parameters. Several curves are offered by the seismic engineering literature, each referring to a specific building structural category. We rely on Asprone et al. (2013) selection of curves, that is reported in Table 4.

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[2] As far as the year of construction concerns, ISTAT does not specify the exact year in which the building has been built, but a time interval which is approximately ten-years long. We assumed that the number of buildings constructed in any year of the interval is constant.

Table 4: Fragility curves for seismic risk assessment.

Structure	Model (k)	N_{LS_k}	gravity load		seismic load	
			μ	σ	μ	σ
Masonry	Rota, Penna, and Strobbia (2008)	3			-2.03	0.36
					-1.65	0.27
					-1.35	0.22
	Ahmad, Crowley, and Pinho (2011)	4			-1.13	0.35
					-1.03	0.35
					-0.85	0.26
					-0.77	0.23
	Erberik (2008)	2			-0.47	0.35
					-0.33	0.35
	Lagomarsino and Giovinazzi (2006)	3			-1	0.41
					-0.75	0.34
					-0.61	0.37
	Rota, Penna, and Magenes (2010)	3			-0.85	0.24
					-0.7	0.18
					-0.58	0.14
Reinforced Concrete	Kappos, Panagiotopoulos, et al. (2003)	4	-1.78	1.14	-1.32	0.29
			-1.12	0.8	-0.95	0.27
			-0.7	0.63	-0.57	0.27
			-0.59	0.57	-0.24	0.28
	Spence (2007)	4	-1.01	0.32	-0.87	0.29
			-0.55	0.32	-0.46	0.28
			-0.28	0.31	-0.02	0.29
			-0.09	0.32	0.15	0.27
	Crowley et al. (2008)	2	-0.77	0.24	-0.8	0.18
			-0.62	0.26	-0.61	0.22
	Ahmad, Crowley, and Pinho (2011)	3	-1.07	0.22	-1.07	0.22
			-0.91	0.29	-0.91	0.29
			-0.59	0.26	-0.44	0.26
	Borzi, Crowley, and Pinho (2007)	2	-0.74	0.32	-0.56	0.32
			-0.46	0.34	-0.37	0.33
	Borzi, Crowley, and Pinho (2008)	2	-0.68	0.45	-0.41	0.35
			-0.41	0.36	-0.31	0.35
	Kostov et al. (2004)	3	-0.48	0.47	-0.44	0.48
			-0.34	0.48	-0.28	0.49
			-0.29	0.48	-0.19	0.49
	Kwon and Elnashai (2006)	2	-1.08	0.22		
			-0.73	0.22		
	Ozmen et al. (2010)	2	-0.37	0.35	-0.36	0.3
			-0.17	0.23	-0.12	0.15
	Kappos, Panagopoulos, et al. (2006)	4	-1.57	0.44	-1.14	0.43
			-0.92	0.44	-0.57	0.43
			-0.67	0.44	-0.18	0.43
			-0.51	0.44	0.1	0.43
	Tsionis, Papailia, and Fardis (2011)	2	-0.67	0.27	-0.64	0.28
			-0.22	0.38	0.18	0.79
Other	Kostov et al. (2004)	3	-0.62	0.5	-0.52	0.49
			-0.44	0.49	-0.34	0.49
			-0.35	0.49	-0.24	0.49

Note: this Table reports the selection of seismic fragility curves per building structural typology by Asprone et al. (2013).

The selection contains 5 models for masonry structures, 11 for reinforced concrete ones, and 1 for the other typology. Each model k is defined on a different set of N_{LS_k} limit states representing building's structural damage conditions (the last limit state always corresponds to collapse) and provides one fragility curve for each limit state. Our fragility curves are log-normally shaped and require PGA values as unique input.

3.3.4 Loss

The loss component is represented by the function $RC(LS)$ transforming structural damages into monetary losses. We assume that the property value equals its reconstruction cost - on average 1500 euro per square meter, constant among all the municipalities (Agenzia delle Entrate, 2015) - and define $RC(LS)$ as a fraction of the total reconstruction cost RC through a function $RC(LS)$:

$$RC(LS) = \left(\frac{LS}{N_{LS_k}} \right)^{\alpha} RC. \tag{3.5}$$

where each limit state is represented by a positive integer and N_{LS_k} is the number of limit states of model k. According to Asprone et al. (2013), we assume $\alpha = 1$.

3.4 Flood

Hydraulic literature offers very little about flood damage in Italy because the lack of uniform data at national level hinders research in this field. A few studies concern small geographical areas (usually cities, sometimes sections of river basins) and focus on the estimation of damages in the immediate follow-up of an event. Most of the analysis study the relationships between some flood's physical measurements and expected losses, and the most common output are depth-percent damage curves. Machine learning techniques have been recently applied to the creation of river basins hazard maps (Degiorgis et al., 2012; Gnecco et al., 2017). However, these techniques still require quite accurate data on past loss. Few example of probabilistic risk assessment have been developed for other countries also, and, similarly to Apel et al. (2006), we decided to extend the deterministic post-event models available in the literature to probabilistic assessment. In this respect, we estimated expected losses by means of depth-percent damage curves from the existing literature and additional information on hazard and exposure from our database. In particular, two functions characterize our model: depth damage curves $g(\cdot)$ and depth probability, that might be represented by the density $f_\delta(\delta)$, the cumulative distribution $F_\delta(\delta)$ and the exceedance probability $\lambda(\delta) = 1 - F_\delta(\delta)$.

Like seismic fragility curves, depth-damage curves refer to structural typologies. In particular, we consider the buildings' number of storeys and classify the housing stock into 3 classes (j) - 1, 2 and 3 or more storeys . A sample of depth-damage curves $g_j(\delta)$ has been selected from the engineering literature per each structural typology j. Unlike seismic fragility curves, depth-damage curves do not specify the probability that a given level of depth might produce a certain damage and return the most likely outcome only. Moreover, the selected curves are "depth-percent damage", and indicate damages as percentages of property's total value.

Given the building's reconstruction cost RC, expected flood loss per square meter $l^f_{j,c}$ on a j-type building in the municipality c can be estimated as:

$$\begin{aligned} l^f_{j,c} =& \frac{RC}{100} \int_0^\infty \left[g_j(\delta) \left| \frac{\mathrm{d}\left(\lambda\left(\delta\right)\right)}{\mathrm{d}\delta} \right| \right] \mathrm{d}\delta = \\ =& \frac{RC}{100} \int_0^\infty \left[g_j(\delta) \left| \frac{\mathrm{d}\left[1 - F_\delta(\delta)\right]}{\mathrm{d}\delta} \right| \right] \mathrm{d}\delta = \\ =& \frac{RC}{100} \int_0^\infty g_j(\delta) f_\delta(\delta) \mathrm{d}\delta. \end{aligned} \tag{3.6}$$

By construction, there is a value $\delta_{j,max}$ after which a $g_j(\delta) = 100$. Thus, equation (3.6) can be split in two parts as:

$$l^f_{j,c} = \frac{RC}{100} \cdot \left[\int_0^{\delta_{max}} g_j(\delta) f_\delta(\delta) \mathrm{d}\delta + 100 \cdot \int_{\delta_{max}}^\infty f_\delta(\delta) \mathrm{d}\delta \right]. \tag{3.7}$$

Bayes' theorem allow us to express $f_\delta(\delta)$ as the product of the probability of δ conditional to the occurrence of at least a flood event $f_{\delta|N_F}(\delta|N_F \geq 1)$ and the probability that at least one flood event occurs in a year:

$$f_\delta(\delta) = P(N_F \geq 1) f_{\delta|N_F}(\delta|N_F \geq 1). \tag{3.8}$$

When estimating losses, we are considering $N_F \geq 1$ only, thus substituting eq. (3.8) into eq. (3.7) leads to:

$$\begin{aligned} l^f_{j,c} = \frac{RC}{100} \cdot P(N_F \geq 1) \cdot \Bigg[\int_0^{\delta_{max}} & g_j(\delta) f_{\delta|N_F}(\delta|N_F \geq 1)\mathrm{d}\delta + \\ & +100 \cdot \int_{\delta_{max}}^{\infty} f_{\delta|N_F}(\delta|N_F \geq 1)\mathrm{d}\delta \Bigg]. \end{aligned} \tag{3.9}$$

Since

$$\begin{aligned} \int_{\delta_{max}}^{\infty} f_{\delta|N_F}(\delta|N_F \geq 1)\mathrm{d}\delta = & 1 - F_{\delta|N_F}(\delta_{max}|N_F \geq 1) = \\ & = \lambda_{\delta|N_F}(\delta_{max}|N_F \geq 1) \end{aligned} \tag{3.10}$$

the model becomes:

$$\begin{aligned} l^f_{j,c} = \frac{RC}{100} \cdot P(N_F \geq 1) \cdot \Bigg[\int_0^{\delta_{max}} & g_j(\delta) f_{\delta|N_F}(\delta|N_F \geq 1)\mathrm{d}\delta + \\ & +100 \cdot \lambda_{\delta|N_F}(\delta_{max}|N_F \geq 1) \Bigg]. \end{aligned} \tag{3.11}$$

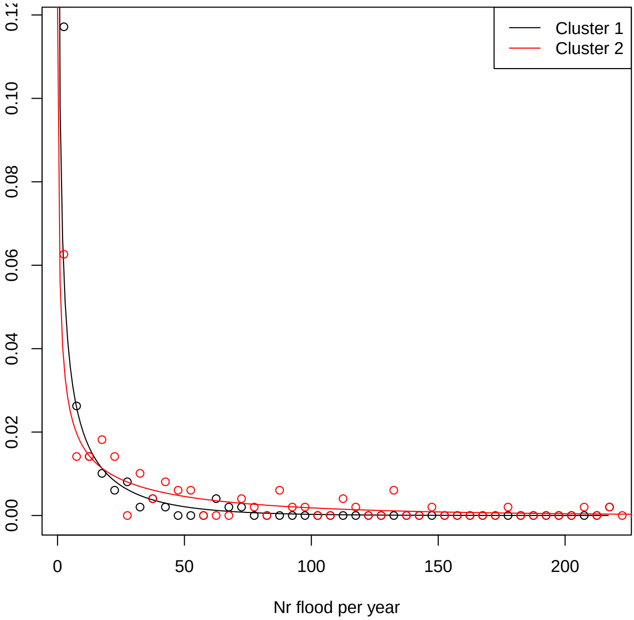
Loss estimates per square meter per municipality and structural typology are multiplied by municipal exposure and aggregated into municipal flood losses L^f_c

$$L^f_c = \sum_{j=1}^{3} l^f_{j,c} \cdot E^f_{j,c}. \tag{3.12}$$

3.4.1 Hazard

Flood hazard has been represented by frequency and depth probabilities. Both the distributions have been estimated from the AVI database and fitted by means of non-parametric techniques due to the lack of data. Since AVI gathers information from local press, it is likely that most remote events have not been captured. In particular, the number of floods listed after 1900 in the AVI archive is much higher than those recorded before and therefore we considered events occurred from that date onward only. Unfortunately, only 795 events remain, and they are too few to fit distributions at municipal level.

Figure 2: Flood frequency distribution.

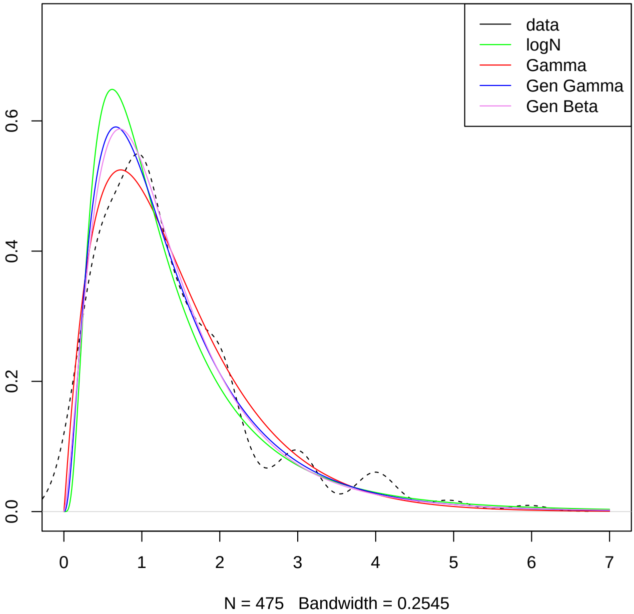


Note: the plot divides observations (points) in two clusters: records from municipalities with $0 < P2 < 0.5$ and $P2 \geq 0.5$. Both the clusters have been fitted with a negative binomial, as shown by the black and red lines.

Frequency has been described by the probability density function of the number of floods in a year $f_{N_F}(N_F)$. In order to capture differences between the frequency of occurrence among the municipalities, data have been divided into two clusters - A_{P_1} (120 obs.) and A_{P_2} (620 obs.) - on the basis of the hydrological hazard index $P2$ from MRCI. Figure 2 shows that frequencies $f_{N_F}^{A_P}$ approximate negative binomial behavior in both the two clusters. Despite the curves appear so close, they strongly differ in mean (the average number of floods per year is 11.95 in A_{P_1} and 42.58 in A_{P_2}).

The probability of flood returns in each cluster is then adapted to fit the municipal and individual risk: since each flood involves a certain number of municipalities within the cluster A_P, the municipal probability of experiencing at least one flood in a year is estimated by multiplying

Figure 3: Depth probability distribution.



Note: the dotted line is the empirical distribution $f_{\delta|N_F}(\delta|N_F \geq 1)$, and colored lines shows fitting.

$f_{N_F}^{A_P}$ times the average number $\bar{c}^f$ of municipalities flooded in A_P over the number of municipalities $N_c^{A_P}$ in A_P:

$$F_{N_F}^{c}(1) = \left(1 - f_{N_F}^{A_P}(0)\right) \frac{\bar{c}^f}{N_c^{AP}} \qquad c \in A_P. \tag{3.13}$$

Floods usually strike several municipalities at the same time, but not all the properties in a flooded municipality will be hit by the flood. Therefore, the individual flood frequency does not coincide with the municipal one. We approximated the individual frequency probability by means of the $P3$ index in MRCI[3], that indicates the percentage of municipal surface flooded in a 20-50 years probabilistic scenario. We indicate the index as

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[3] Indicators P3 are not available for the entire Italian territory, since data are missing for part of Marche and Emilia-Romagna Regions.

ext_{P3}. Assuming homogeneously distributed buildings among the municipal area, the individual probability of flood returns is:

$$P(N_F \geq 1) = F^c_{N_F}(1) \cdot ext_{c,P3}. \tag{3.14}$$

In addition to frequency, we estimate the probability of water to reach a certain depth during a flood. Depth information are missing for most of the events in the AVI database and sometimes are replaced by hydrometric heights measuring water depth from the riverbed. We excluded hydrometric heights and assumed that depth levels reported in the database always correspond to the maximum reached in the area, which is a reasonable hypothesis since records in AVI are largely gathered from local press or compensation claims.

We found no significant difference in depth distributions between differently-exposed areas A_P but this may be due to the low amount of available data, and therefore decided to estimate a unique function $f_{\delta|N_F}(\delta|N_F \geq 1)$ for the entire national territory. Since a flood usually hits more municipalities, a number of depth measurements are often reported for the same event, but we represented each event with the maximum depth reported in the database. Hence, estimates have been computed on 475 observations.

The depth empirical distribution estimated from AVI data $f_{\delta|N_F}(\delta|N_F \geq 1)$ is shown in Figure 3, where a graphical comparison between some distributions is presented too. Satisfactory fittings have been reached with the Generalized Beta (GB), the Generalized Gamma (GG) and the Gamma distributions. Table 5 shows that GG and GB's led to similar sum of squared errors and sum of absolute errors, while errors are much higher for the Gamma. The Chi squared goodness of fit test confirms the higher performance of GG and GB with respect to the Gamma, even though none of them reached a positive outcome. However, the likelihood ratio test shows weak evidence that the GG is more appropriate, therefore the Gamma has been chosen because of computational advantages.

3.4.2 Exposure

When evaluating structural vulnerability to floods, the number of storeys of the building is a fundamental feature to take into account. Therefore, buildings have been classified in three groups according to the number of storeys - one, two and three or more - in MRCI. Another

Table 5: Flood depth distribution, goodness of fit.

	SSE	SAE
Gamma	0.02194857	0.2493763
GG	0.01328367	0.1951612
GB	0.01444061	0.2024778

Note: this Table shows the sum of squared errors (SSE) and sum of absolute errors (SAE) obtained when fitting flood depth distribution with Gamma, Generalized Gamma (GG) and Generalized Beta (GB) distributions.

element significantly affecting buildings resistance to floods is the presence/absence of a basement floor; since this information is not available, we assumed the two features to be equally distributed.

Given the number of buildings per structural typology within the municipality $B_{j,c}$, the average number of apartments per building $\bar{A}_c$ (ISTAT, census 2015) and the average apartment's surface $\bar{s}_c$ (Agenzia delle Entrate, 2015), exposure has been estimated as:

$$E^f_{j,c} = \bar{s}_c \cdot B_{j,c} \cdot \bar{A}_c. \tag{3.15}$$

Table 6: Number of buildings per number of storeys.

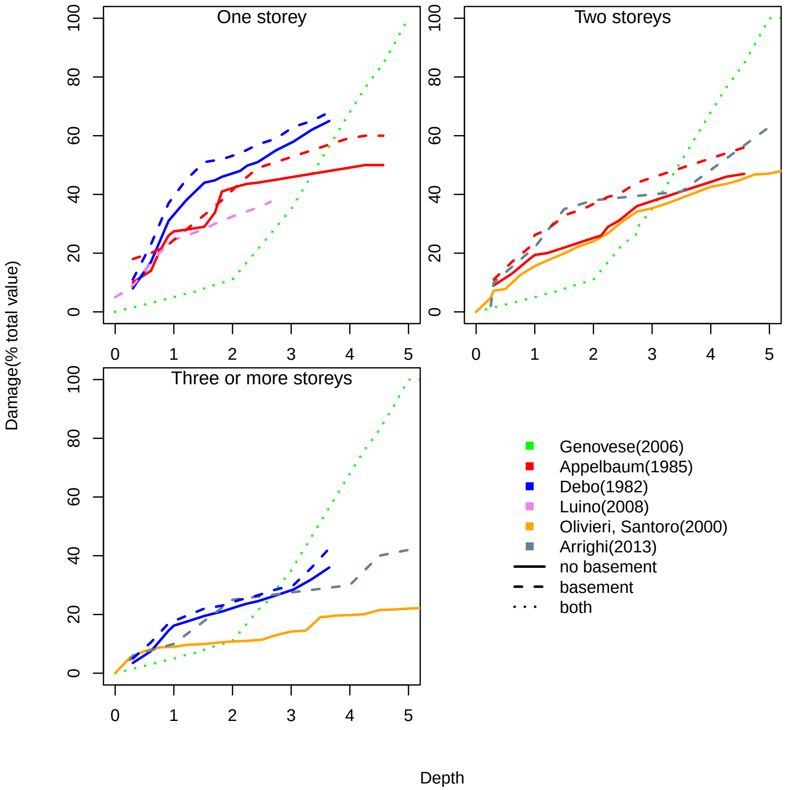
Number of Storeys	Buildings (u=1000)
1	2083.39
2	5981.26
3 or more	4123.05

3.4.3 Vulnerability

Flood's vulnerability is evaluated by depth damage curves defined on the building's number of storeys. The most widely adopted curves in hydraulic literature express damage as a percentage of building's total value and therefore called "depth-damage curves". Conversely to the curves expressing damages in absolute values, percentages curves are not affected by monetary volatility and are more reliable (Appelbaum, 1985).

Many studies have led to the definition of different depth-percent damage curves, that are strongly geographical-dependent (Scorzini and

Figure 4: Depth-percent damage curves for flood risk assessment.

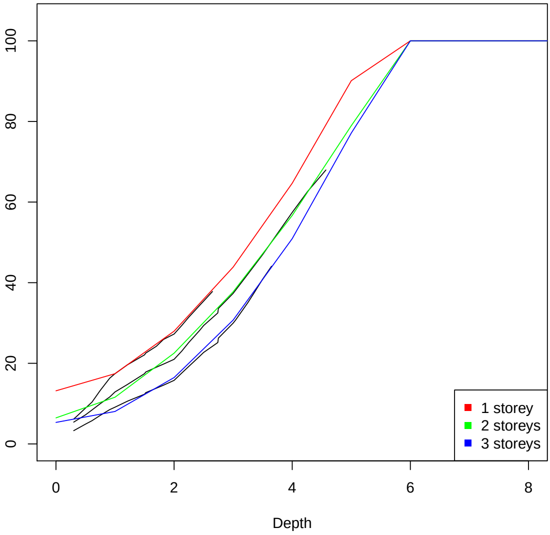


Note: selection of depth-percent damage curves for flood risk assessment. Curves are listed per buildings' number of storeys and can refer to dwellings with and/or without basement.

Frank, 2015): being derived from the analysis of historical data, they are in fact defined on the characteristics of the area under analysis and tend to lose accuracy when applied to contexts whose urban and territorial features differ too much from the original site.

We have selected depth-percent damage curves from six previous works (Appelbaum, 1985; Arrighi et al., 2013; Debo, 1982; Genovese, 2006; Luino et al., 2009; Oliveri and Santoro, 2000), all either defined or

Figure 5: Depth-percent damage curves.



Note: black lines represent the average values of the curves selected per number of storeys. Red, green and blue lines show the functions fitted by polynomial regression.

tested on Italian data. The selection is reported in Figure 4. Selected curves per structural typology have then been averaged into three new curves in order to guarantee higher reliability of results at the national level. Curves have been fitted by polynomial regressions, as shown in Figure 5.

3.4.4 Loss

Structural damages have been converted into monetary terms by means of the function $\frac{RC}{100}$. Similar to the seismic model, we assume that the property value is equal to its reconstruction cost - on average 1500 euro per square meter, constant among all the municipalities (Agenzia delle Entrate, 2015).

3.5 Results

Earthquake and flood losses have been estimated per municipality and structural typology. Seismic risk is described in Table 8, where results from Asprone et al. (2013) are also reported for comparison. We can note that, though the model adopted is the same, huge differences emerge between the two analysis. Several reasons contribute to these discrepancies and should be discussed for a better understanding of results.

First of all, (i) estimates are highly sensitive to the probability distribution of hazard intensities, and while $\lambda(PGA)$ has been here fitted from INGV data, Asprone et al. (2013) rely on some distributional assumption. In addition, (ii) we assumed PGA values ranging in $[0, \infty]$, while the previous analysis considers $[0, 2g]$ only. (iii) INGV data on PGA fails to represent many smaller municipalities that have here been approximated by means of neighbors' values and this assumption may have further contributed to the differences in results. (iv) Exposure strongly affect results too and while MRCI collects the number of dwellings per structural typology at the municipal level, Asprone et al. (2013) had information at the provincial level only. Moreover, MRCI refers to the 2011 population census, while the database used by Asprone et al. (2013) date back to 10 years earlier.

Arguments (i)-(iv) determine the different loss scenario, and, in particular, Table 8 shows that estimated loss per square meter obtained by our model are considerably lower than those of Asprone et al. (2013). The main reason is the adoption of a power law distribution that concentrates the probability on weaker events. However, our model highlights the gap in expected losses between more and less fragile buildings more than the older version.

Though our losses per square meter are lower than previous findings, the second column of the Table 8 ($\max(l^s_{j,c})$) describe similar patterns. By contrast, expected losses per municipality and structural typology $L^s_{j,c}$ in the third column do not even show the same pattern. As argued before, exposure strongly affect results and the detailed information on buildings in MRCI allowed us to better represent real estate assets. In fact, Rome is the biggest municipality in Italy, and therefore its exposure produces expected losses that are extremely higher than those of other municipalities. By contrast, the homogeneous distribution of provincial structures among the municipalities in Asprone et al. (2013) very likely underestimates the exposure of major areas.

The fundamental role of exposure becomes clear when comparing $l^s_{j,c}$ and $L^s_{j,c}$ geographically. Figure 6 represents the expected loss per square meter on the most vulnerable buildings - the masonry structures - in each municipality. The map reflects the hazard component of the risk model and clearly shows the proximity to risk sources. By contrast, this pattern in risk distribution is not evident in Figure 7 showing annual total expected losses per municipality. In fact, the risky dark area delimited in Figure 6 largely corresponds to the Appennino mountain chain, where several municipalities are sparsely inhabited. On the other hand, densely populated municipalities on the coast do not show extremely high level of loss per square meter but reach the highest expected losses at the aggregate level because of large real estates.

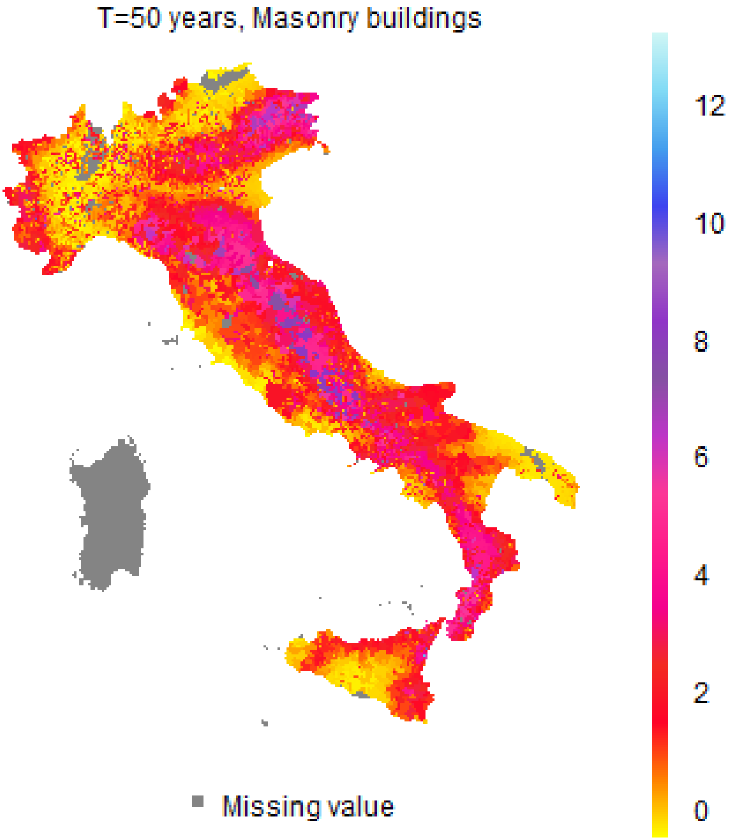
In order to appreciate the effect of different hazard and exposure components, one can consider reinforced concrete gravity loaded structures: though the power law distribution gets to a lower $\max(l^s_{j,c})$, the associated estimate of the expected loss $L^s_{j,c}$ in Rome is four times greater than that obtained in the previous paper.

Our analysis of seismic risk led to total expected loss equal to 6234.66 million, which is almost half the value obtained by Asprone et al. (2013). The value is seven times greater than the expected loss estimated for flood risk, equal to 875.90 million per year, thus indicating that the earthquakes are the natural hazard of main concern in Italy.

As far as flood losses concern, main findings are presented in Table 9. Maximum losses per square meter $l^f_{j,c}$ are higher than the seismic ones, but Figure 8 shows that a great part of the territory does not appear to be affected by hydrological risk and most municipalities are associated to values of $l^f_{j,c}$ close to 0. The map shows that the risk mostly affects northern Italy, and in particular the Emilia-Romagna, Veneto and Lombardia regions. More or less the same risk distribution is obtained at the aggregate level in Figure 9, where the effect of exposure highlights additional areas of interest, such as the north-west coast, north Sardinia and Rome.

By comparing Figures 7 and 9, we can observe that north-east Italy is highly affected by both the two hazards, though the effect of floods remains consistently limited with respect to that of earthquakes. To conclude, Table 7 ranks the fifteen largest expected municipal losses per each hazard. One can notice that three cities in Emilia-Romagna are listed for both: Bologna, Ravenna and Rimini.

Figure 6: Seismic expected loss per square meter (masonry buildings).



Note: the minimum value is $l^s_{j,c} = 0.025$, maximum is 12.69, and average value is 2.23 euro per square meter.

Figure 7: Expected seismic annual loss per municipality.

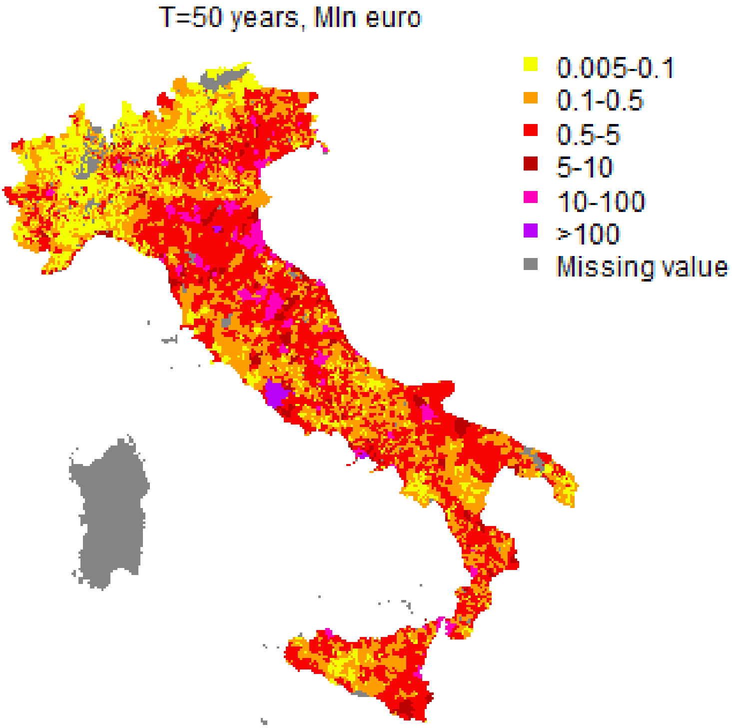
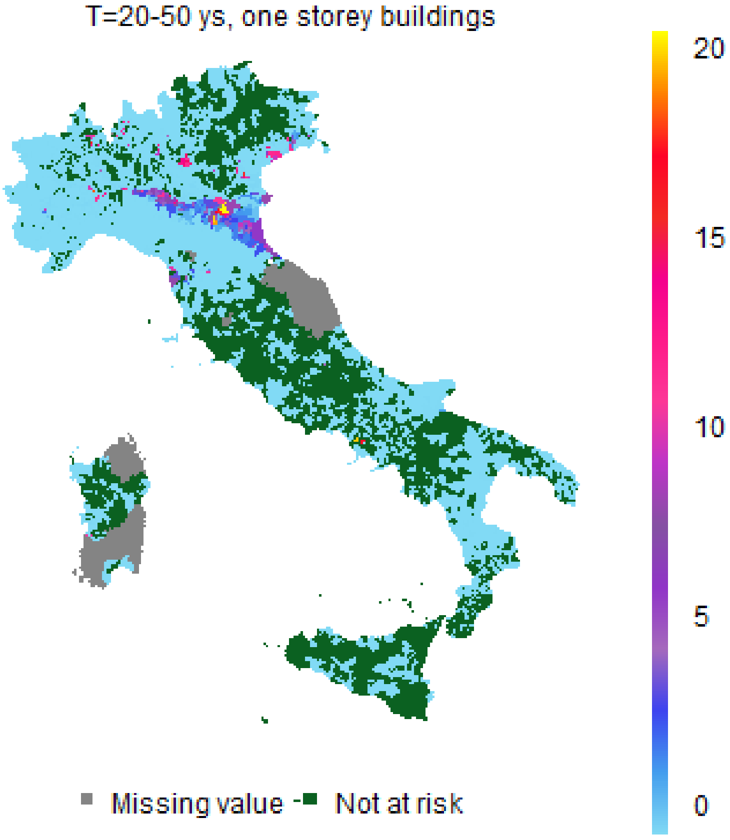


Figure 8: Flood expected loss per square meter (one-storey buildings)



Note: "Not at risk" identifies municipalities where $l^f_{j,c} = 0$. Among the other municipalities, the minimum loss is $2.24e^{-08}$. Maximum value is $l^f_{j,c} = 19.61$. On average, expected loss in risky areas (municipalities "Not at risk" not included) is 0.37 euro per square meter.

Figure 9: Expected flood annual loss per municipality.

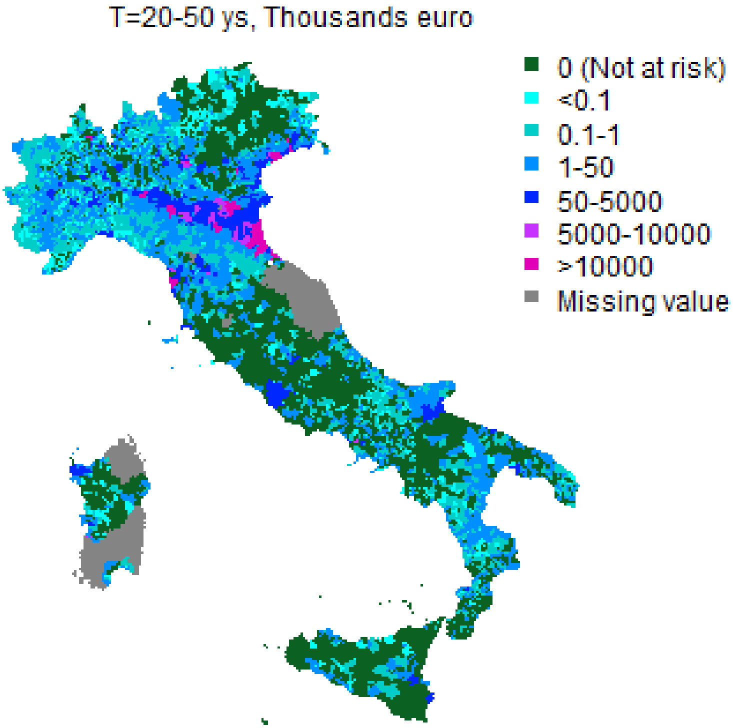


Table 7: Municipalities with higher expected loss per natural risk.

	Seismic Expected Loss			
	Municipality	Province	Region	L_c^s(Mln euro)
1	Roma	Roma	Lazio	337.46
2	Napoli	Napoli	Campania	114.03
3	Bologna	Bologna	Emilia-Romagna	105.26
4	Verona	Verona	Veneto	59.58
5	Firenze	Firenze	Toscana	58.55
6	Torino	Torino	Piemonte	45.17
7	Reggio di Calabria	Reggio di Calabria	Calabria	43.23
8	Modena	Modena	Emilia-Romagna	39.57
9	Prato	Prato	Toscana	33.36
10	Terni	Terni	Umbria	33.03
11	Ravenna	Ravenna	Emilia-Romagna	31.69
12	Rimini	Rimini	Emilia-Romagna	30.38
13	Messina	Messina	Sicilia	29.92
14	Pistoia	Pistoia	Toscana	29.50
15	Catania	Catania	Sicilia	29.14

	Flooding Expected Loss			
	Municipality	Province	Region	L_c^f(Mln euro)
1	Ferrara	Ferrara	Emilia-Romagna	56.22
2	Ravenna	Ravenna	Emilia-Romagna	52.89
3	Rimini	Rimini	Emilia-Romagna	45.03
4	Pisa	Pisa	Toscana	37.33
5	San Michele al Tagliamento	Venezia	Veneto	34.48
6	Jesolo	Venezia	Veneto	27.83
7	Parma	Parma	Emilia-Romagna	23.51
8	Bologna	Bologna	Emilia-Romagna	21.63
9	San Donà di Piave	Venezia	Veneto	21.31
10	Cesenatico	Forlì-Cesena	Emilia-Romagna	17.02
11	Piacenza	Piacenza	Emilia-Romagna	16.05
12	Cervia	Ravenna	Emilia-Romagna	15.40
13	Verbania	Verbano-Cusio-Ossola	Piemonte	14.58
14	Forlì	Forlì-Cesena	Emilia-Romagna	13.33
15	Abano Terme	Padova	Veneto	12.94

Table 8: Estimated seismic expected losses.

	Structure	$\max(l^s_{j,c})$ (euro)	$\max(L^s_{j,c})$(Mln euro)	tot L^s_j (Mln euro)
$\lambda(PGA) \sim PL$	RC.gl	10.53 Castelbaldo (Padova)	216.79 Roma	2223.61
	RC.sl	3.83 Castelbaldo (Padova)	3.54 Roma	130.70
	A.gl	4.03 Castelbaldo (Padova)	7.16 Roma	233.76
	A.sl	3.22 Castelbaldo (Padova)	0.43 Roma	30.73
	M	12.69 Castelbaldo (Padova)	109.54 Roma	3615.87
	tot			6234.661
Asprone (2013)	RC.gl	17.04 Giarre (Catania)	51.5 Roma	1186.8
	RC.sl	11.34 Navelli (L'Aquila)	8.0 Reggio di Calabria	489.9
	A.gl	14.51 Giarre (Catania)	25.1 Roma	667.2
	A.sl	11.71 Navelli (L'Aquila)	2.4 Napoli	174.0
	M	29.99 Giarre (Catania)	196.4 Roma	8661.8
	tot			11179.6

Note: the table lists some descriptive statistics about estimated seismic expected losses per structural typology; in order: maximum expected loss per square meter $l^f_{j,c}$, maximum expected loss at the municipal level $L^s_{j,c}$ and the total expected loss L^s_j. The upper part describes current results, obtained by fitting PGA with a power law distribution; the lower side reports results by Asprone et al. (2013) for comparison.

Table 9: Estimated flood expected losses.

Structure	$\max(l^f_{j,c})$(euro)	$\max(L^f_j)$(Mln euro)	tot L^f_j(Mln euro)
1 storey	19.61 Vigarano Mainarda (Ferrara)	7.93 S. Michele al T. (Venezia)	105.75
2 storeys	15.16 Vigarano Mainarda (Ferrara)	36.53 Ferrara	536.14
3 storeys	11.56 Vigarano Mainarda (Ferrara)	18.24 Rimini	234.01
tot			875.90

Note: the Table shows descriptive statistics of flood expected losses per number of storeys. In order: maximum expected loss per square meter $l^f_{j,c}$, maximum expected loss at the municipal level $L^f_{j,c}$ and the total expected loss L^f_j.

3.6 Uncertainty

The estimates obtained by the earthquake and flood models are built on a set of hypotheses and parameters and are therefore uncertain.

An effective analysis to test the predictive capacity of a model is to compare its estimates with the losses recorded from past events. However, it is not easy to find records that can be used for this comparison: especially in countries where insurance does not reach high penetration rates, the losses suffered by private buildings are difficult to trace. Typically, the amounts of public funds devolved for emergencies are available, which however do not represent the entire value lost by the householders and often include the reconstruction of public goods and services too. Moreover, even when suitable records are available, this analysis allows to test all the components of the model except the hazard. Since the exposure, vulnerability and loss components in the present model are specified as in Asprone et al. (2013)[4], we can refer to the analysis on the L'Aquila earthquakes in 2009 and Molise in 2002 in Asprone et al. (2013), the outcome of which suggests that the model has a satisfactory descriptive capacity of the phenomenon.

As clearly shown in Table 8, the expected annual loss that we obtain strongly diverge from that presented in the previous work and the model therefore appears very sensitive to the distribution chosen to represent the earthquake's probability of occurrence. Unlike Asprone et al. (2013), however, our choice is supported by a fitting analysis which, although not parametric, certainly allows a better representation of the phenomenon. The choice of a power law distribution is also consistent with the prevailing literature. Finally, it is interesting to note that IVASS - the national Insurance Supervisory Institute - estimates the average annual loss on residential buildings due to seismic events in Italy equal to 4.7 billion of Euro[5]. This value is quite close to the 6.2 billion we obtained with the power law distribution, and very far from the 11.1 estimated in Asprone et al. (2013).

As far as flood analysis concerns, the lack of records is once again a major obstacle to the robustness analysis of the model and it is not

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[4] The exposure does not perfectly coincide, but the data used in this analysis are taken from the most updated release of the database used in the previous work. As the earthquakes used by Asprone et al. (2013) for the comparison happened before the last release of the census and reshaped the local building estate, the previous database surely suits better for the test, but might be less accurate for prediction today.

[5] See Cesari and D' Aurizio (2019), pp. 35.

Figure 10: Total expected losses as estimated by fitting the distributions over all except one year of observations in the AVI database.

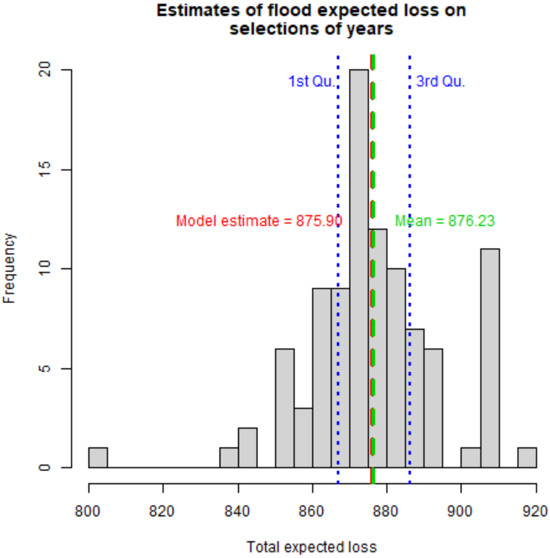
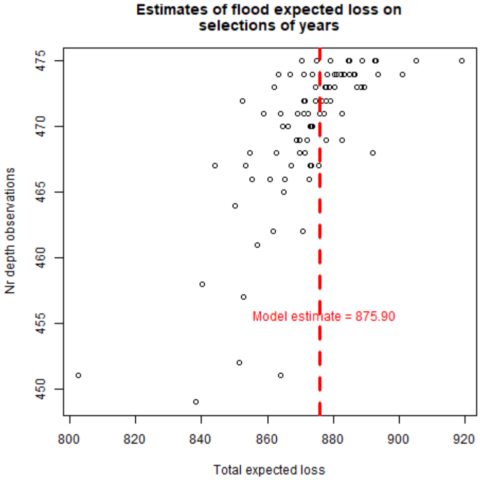
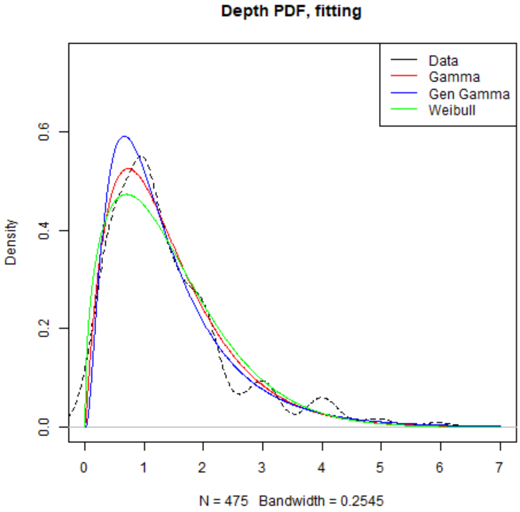


Figure 11: Total expected losses as estimated by fitting the distributions over all except one year of observations in the AVI database compared to the number of depth observations available.



possible for us at the moment to compare the estimates with recent past events. As shown by de Moel et al. (2015), modelling flood risk involves various sources of uncertainty and it is often impossible to accurately verify the predictive capacity of a model. Although this is not sufficient to ascertain the robustness of our estimates, it is important to underline that all depth-damage curves used in this study have been tested on past events. Readers may refer to the related sources to check out on these analyses.

Due to the lack of data on floods in Italy, official estimates of losses are also rather scarce. To our knowledge, the only report in this regard is ANIA and Guy Carpenter (2011), which estimates the residential losses generated exclusively by river flooding equal to 230 million euros per year. This figure is not in itself comparable with our estimate, which instead represents the losses generated by any type of alluvial phenomenon, including flash floods and other intense rainfall events that often affect the Country, but it is actually compatible. Moreover, the report also estimates that the expected losses due to river floods constitute about 8% of the total annual expected loss generated by both river floods and earthquakes. Our results suggest that this ratio, evaluated considering any flood type, is approximately equal to 12%, and is therefore very similar to the results in ANIA and Guy Carpenter (2011).



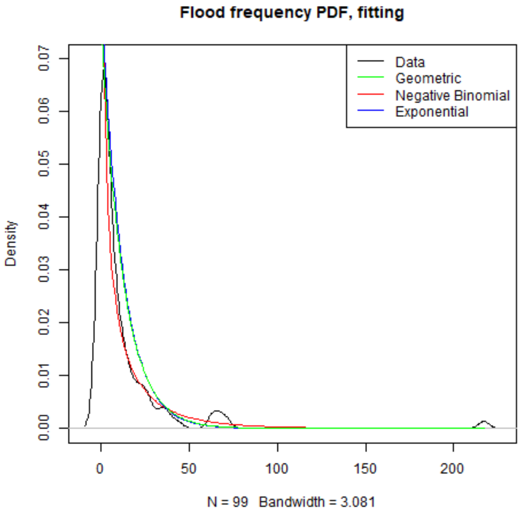
	Gamma	Generalized Gamma	Weibull
$\max(l^f_{1s,c})$	19.61	19.80	19.68
$\max(l^f_{2s,c})$	15.16	15.34	14.90
$\max(l^f_{3+s,c})$	11.56	11.82	11.39
L^f (mln)	875.90	888.38	863.62
Variation in L^f		+1.42%	-1.40%

Table 10: Sensitivity analysis of the flood model to the choice of the distributional form of depth.

Flood

The uncertainty in the estimates of flood losses can largely be traced back to the hazard component of the model. We fitted the probability distributions for frequency and depth on the AVI database, whose criti-

Figure 12: Fitting of the flood frequency distribution of the first cluster.



Note: a similar plot is obtained for cluster 2.

		Cluster 1			
Distorsion		-1%	-0.5%	+0.5%	+1%
Size	L^f (mln)	875.75	875.83	875.97	876.05
	Variation in L^f	-0.02%	-0.01%	0.01%	+0.02%
Mu	L^f (mln)	875.87	875.89	875.91	875.92
	Variation in L^f	-0.003%	-0.001%	+0.001%	+0.002%

		Cluster 2			
Distorsion		-1%	-0.5%	+0.5%	+1%
Size	L^f (mln)	869.18	872.54	879.25	882.60
	Variation in L^f	-0.77%	-0.38	+0.38%	+0.76%
Mu	L^f (mln)	875.50	875.71	876.08	876.23
	Variation in L^f	-0.05%	-0.02%	+0.02%	+0.04%

Table 11: Sensitivity analysis of flood model to variation in the Negative Binomial parameters.

calities have already been discussed in paragraph 3.2. As typical of flood events, AVI shows a great variability between the years of survey. As shown in Figure 10, excluding one year of observations from the analysis does not overall significantly impact results. Two years exhibit the strongest effect on the model and once excluded lead to the minimum and the maximum expected losses respectively. These two years are 1966 and 1998 respectively, and there is no apparent reason why they should be considered outliers, as no social event (e.g. wars) or change in technology and in the data collection method may have influenced the detection of floods during the two years.

The choice of years to be included in the fitting should be carefully evaluated especially for the depth distribution, for which much less data are available than for frequency. In fact, excluding one year from the database involves a variable reduction in the number of depth observations, precisely equal to the number of floods recorded in the year. Figure 11 compares the models outputs obtained by excluding one year a time with the number of observations available for depth. The plot shows that the fewer observations are considered, the lower the overall loss estimates are. The phenomenon is not surprising, as it is normal for years with greater flood intensity to record both more floods and greater depths. However, it is important to consider that the impact of a decreased sample can be considerable in a context where the information available are already quite scarce. This might be the case, for example, of the minimum total expected losses obtained by excluding 1966. Nevertheless, estimates fluctuate around the mean value, showing a quite limited variability.

Beside the selection of the years in the database, the choice of the flood distributions itself brings additional uncertainty to the model. In particular, in the case of depth, it was possible to identify different distributive forms capable of satisfactorily describing the data. As it can be noted in Table 10, either a generalized Gamma or a Weibull distribution would have been adequate to describe the data, although the first leads to overestimating losses with respect to the Gamma and the second to an underestimate. In both cases, however, the difference in the outcome is only 1.4%.

As far as frequency is concerned, the Negative Binomial distribution achieves the highest goodness of fit and should hence be preferred to any other distributional form. As clearly shown in Figure 12, even the second best distributions - the Geometric and the Exponential - do not properly fit the data, while the Negative Binomial suits them perfectly.

Table 11 shows the sensitivity of the estimates to small variations of the distribution parameters.

3.7 Conclusion

Seismic and flood risks in Italy have been analyzed. Given the limited amount of data available on natural risks, an alternative approach based on risk-modeling has been applied to estimate expected monetary losses. We found that seismic risk results in the highest expected losses at national level, but floods may generate the highest losses per square meter. The two perils differ in geographic extent: while the seismic risk is relevant for almost all the national territory, floods affect a limited area.

Chapter 4

A public-private insurance for natural risks in Italy

This Chapter is a joint work with my supervisors Giorgio Stefano Gnecco and Fabio Pammolli. The full text of the article is also available from the arXiv repository, preprint number 2006.05840.

Abstract

We propose a public-private insurance scheme for earthquakes and floods in Italy in which property-owners, the insurer and the government co-operate in risk financing. Our model departs from the existing literature by describing an insurance scheme intended to relieve the financial burden that natural events place on governments, while at the same time assisting individuals and protecting the insurance business. Hence, the business is aiming at maximizing social welfare rather than profits. In order to evaluate the insurer's loss profile, spatial correlation among insured assets has been included by means of the Hoeffding bound. Though earthquakes generate expected losses that are almost six times greater than floods, we found that the amount of public funds needed to manage the two perils is almost the same.

4.1 Introduction

When constructing an insurance scheme, two fundamental quantities should be carefully evaluated: the premium per policyholder and the amount of reserves needed for the business given the solvency constraint. In the private market, insurers aim at profit and constitutes reserves through premium's collection. Therefore, rates should be sufficiently high to yield profit and avoid unacceptable levels of loss, while at the same time meeting an acceptable level of risk. Moreover, in order for the policy to be purchased, premiums should also meet the demand. Premium rating can hence be represented as a typical decision problem of profit and utility maximizing agents (Mossin, 1968; Ehrlich and Becker, 1972). However, when the government takes over the market, it radically changes the management objectives of the insurance company, and the traditional model is no longer suitable to capture agent's behavior. In this respect, this chapter presents a public-private insurance model for natural disasters where homeowners, insurers and government cooperate in risk financing.

Although the traditional private insurance-model has to be suitably modified to describe a public-private partnership, the problem can still be represented by comparing two perspectives: on the one hand, individuals who are willing to spend up to a certain amount on coverage; on the other hand, the insurer who, supported by the government, offers the policy subject to some solvency constraints. Following the example of some of the strongest public-private insurance systems for natural disasters, we assume that each individual can access to a single policy only and we exclude competing offers. Our model can therefore represent both an insurance monopoly (like Switzerland) or a public-private insurance system with rates set by the State (like Japan). The next two sections address the problem on the demand and supply perspectives respectively.

On the demand side, individuals face a decision problem, and their utility functions can be defined as in the private-market literature. Because the model looks for the maximum amount that individuals are willing to pay, we keep the standard assumption of perfect information and rationality of individuals, though these hypotheses are often criticized as inappropriate to describe real world conditions (Goda, Wenzel, and Daniell, 2015; Skees, Hazell, and Miranda, 1999; Kunreuther and

Pauly, 2004).[1] These criticisms are extremely important for the private market, but might be more easily overcome by governments, as they have a stronger ability to modify the behavior of individuals by investing in risk education or promoting public awareness.

On the supply side, the goal of insurance business is substantially affected by the partnership with the government. In the free market, insurer's goal is profit maximization subject to survival and/or stability constraints that require low ruin probability and low probability of high operational costs (Goda, Wenzel, and Daniell, 2015). By contrast, when entering the business, the government forces insurers to set the lowest premium possible given both the demand and the solvency constraints. Our model departs from traditional literature by assuming that the business endorses social welfare and therefore rates do not include profit-load. On the other side the government also supports the business by relaxing its financial burden: it partially subsidises reserves through capital injections and contributes to the reimbursement whenever stored funds are not sufficient for claim compensation.

Several additional issues arise in specifying the supply side. In particular, insurers' solvency constraint refers to the aggregate loss distribution, which is difficult to represent due to lack of information. While expected losses can be reconstructed through risk modeling as in Chapter 3, particular attention should be devoted to the variance as spatial correlations strongly affect insurer's potential of extreme losses. Quantifying correlation is difficult when records of past events are available, and it is practically impossible when they are not. However, it is reasonable to assume that spatial correlation between municipalities depends on their proximity, so that it can be identified a sufficiently large threshold r such that two municipalities that are at least r-km far away are independent. We assume $r = 50$ km and include spatial correlation by means of the Hoeffding bound for r-dependent variables.

In addition to risk quantification, private insurers are also affected by state regulations, market competition (Grossi, Kunreuther, and Windeler, 2005) and social or political decisions that may result in moral hazard

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[1] Common shared information between insurer and insured is questionable in real contexts (Cooper and Hayes, 1987; Kunreuther and Pauly, 1985). In addition to lack of data for risk assessment, individuals also have to face limited cognitive capacity (Kahneman, 2003; Goda, Wenzel, and Daniell, 2015) and imperfect rationality: Kunreuther (1996) asserts that policy adoption conveys individual risk perception; Palm (1995) observes that appreciation of earthquake policies' benefits depends on personal attitude, socioeconomic and demographic characteristics, proximity to physical hazards, and past experience.

and adverse selection (Kunreuther and Pauly, 2009). Coordinating government and insurers actions can prevent these drawbacks, that should therefore not be included in the public-private model.

Finally, agents' attitudes toward risk should also be carefully evaluated. While in the literature is widespread agreed that homeowners are risk-averse, some evidence suggests that insurers may also exhibit risk-aversion (Gollier, 2013). Actuarial practice also encourages cautious behaviors, emphasizing the importance of adjusting rates by a risk-load component proportional to aggregate loss variance for extraordinary uncertain events such as natural hazards (Kunreuther, 1996; Larsen and Kuzak, 2005). However, by entering the business as a guarantor, the government release the insurer from its strict capital constraint and there is no need for the insurer to over-protect the reserves. We thus assume risk-averse homeowners and a risk-neutral insurer.

The two agent's perspectives are combined in Section 4.4 where the insurance scheme is defined. The application to Italian data is discussed in the following section and results for both the two hazards conclude the chapter. Four different policies have been estimated and, thought seismic risk generates highest expected losses, the analysis shows that almost the same amount of public funds is necessary to manage the two risks. This Chapter discusses single hazards policies only, multi-hazard analysis follows in the next Chapter.

4.2 Homeowner's purchase decision

Since the seminal papers by Mossin (1968) and Ehrlich and Becker (1972), several premium setting models on insurance purchase decision have been developed. These models describe policies offered by the private sector and set premiums by comparing the risk-averse individual's willingness to pay with the profit maximization sought by the insurer. Thought we are considering a public-private partnership, individual's willingness to pay is left substantially unchanged. This section deals with the demand side, defines the utility function of the owners, and gets to the maximum premium that they are willing to pay.

Let us consider a single peril insurance (i.e. earthquakes or floods only) in Italy. Any generic homeowner i has an m_i square meters property. The N_i individuals gather in municipalities, thus any i belongs to a generic Italian municipality c. A negative event has an annual probability $1 - \pi_c(0)$ to hit the Municipality c and ruin the i-th individual property at time t causing a loss $l^a_{i,t}$ per square meter. Consider discrete time period t equal to one year.

Individual i may incur in a loss $l^a_{i,t}$ with probability $1-\pi_c(0)$, $i \in c$. This loss affects his wealth $w_{i,t}$, that we assume equal to the house value for simplicity. However, the individual may buy an insurance coverage and pay a premium $p_{i,t}$ per square meter to get a reimbursement $x_{i,t}$ per square meter in case that the event occurs. Let us define $x_{i,t}$ as a function of the actual loss $l^a_{i,t}$:

$$x_{i,t} = \begin{cases} 0, & \text{with probability } \pi_c(0), \\ x\left(l^a_{i,t}\right), & \text{with probability } 1-\pi_c(0), \end{cases} \tag{4.1}$$

where

$$0 < x\left(l^a_{i,t}\right) \leq l^a_{i,t}, \quad i \in c, \tag{4.2}$$

with

$$x\left(l^a_{i,t}\right) = \begin{cases} 0 & \text{if } l^a_{i,t} \leq D, \\ l^a_{i,t} - D & \text{if } D < l^a_{i,t} < E + D, \\ E & \text{if } l^a_{i,t} \geq E + D, \end{cases} \tag{4.3}$$

where D and E are the deductible and the maximum coverage provided per square meter by the insurer.

The homeowner's utility of not being insured is traditionally expressed as the sum of two components representing the case of no events occurring during the year and a unique loss scenario:

$$U_{\text{not insured}} = \pi_c(0)u(w_{i,t}) + (1-\pi_c(0))\, u(w_{i,t} - l^a_{i,t}m_{i,t}). \tag{4.4}$$

Similarly, the utility of purchase is defined as:

$$\begin{aligned} U_{\text{insured}} =& \pi_c(0)u(w_{i,t} - p_{i,t}m_{i,t}) + \\ & + (1-\pi_c(0))u(w_{i,t} - p_{i,t}m_{i,t} - l^a_{i,t}m_{i,t} + x\left(l^a_{i,t}\right)m_{i,t}). \end{aligned} \tag{4.5}$$

Therefore, assuming rational behavior, we can assume that the homeowner will buy an insurance coverage for its property if and only if its utility of purchasing is greater than or equal to that of not purchasing the policy: $U_{\text{insured}} \geq U_{\text{not insured}}$.

Considering any possible loss level, hence any possible phenomena intensity ζ, we can define the probability $\pi_c(\zeta)$ that c will experience a ζ-intensity event in a year and that the homeowner i living in municipality

c will suffer a loss $l^a_{i,t}(\zeta)$ expressed as a function of ζ. In case he is owning a residential insurance coverage, its claim value will be then:

$$x_{i,t} = \begin{cases} 0, & \text{with probability } \pi_c(0), \\ x\left(l^a_{i,t}(\zeta)\right), & \text{with probability } \pi_c(\zeta), \end{cases} \tag{4.6}$$

where

$$0 < x\left(l^a_{i,t}(\zeta)\right) \leq l^a_{i,t}, \quad \text{with } i \in c \tag{4.7}$$

with

$$x\left(l^a_{i,t}(\zeta)\right) = \begin{cases} 0 & \text{if } l^a_{i,t}(\zeta) \leq D, \\ l^a_{i,t}(\zeta) - D & \text{if } D < l^a_{i,t}(\zeta) < E + D, \\ E & \text{if } l^a_{i,t}(\zeta) \geq E + D \end{cases} \tag{4.8}$$

and the insured purchase-convenience condition becomes:

$$\begin{aligned} \pi_c(0) \cdot u(w_{i,t}) + \int_0^\infty \pi_c(\zeta) \cdot u(w_{i,t} - l^a_{i,t}(\zeta) m_{i,t}) \mathrm{d}\zeta \\ \leq \pi_c(0) \cdot u(w_{i,t} - p_{i,t} m_{i,t}) + \int_0^\infty \pi_c(\zeta) \cdot \\ u(w_{i,t} - p_{i,t} m_{i,t} - l^a_{i,t}(\zeta) m_{i,t} + x\left(l^a_{i,t}(\zeta)\right) m_{i,t}) \mathrm{d}\zeta. \end{aligned} \tag{4.9}$$

According to the traditional literature on insurance purchasing decision, we assume the individual to be risk-averse and we represent its preferences by means of the utility function $u(x) = \log(x+1)$. We set $w_{i,t}$ equal to the house value and assume for simplicity that it corresponds to the reconstruction cost, equal to RC per square meter. The logarithmic specification allows us to simplify the model considering losses per square meter, so we can rewrite eq. (4.9) as:

$$\begin{aligned} \pi_c(0) \cdot \log(RC + 1) + \int_0^\infty \pi_c(\zeta) \log(RC - l^a_{i,t}(\zeta) + 1) \mathrm{d}\zeta \\ \leq \pi_c(0) \cdot \log(RC - p_{i,t} + 1) + \\ \int_0^\infty \pi_c(\zeta) \log(RC - p_{i,t} - l^a_{i,t}(\zeta) + x\left(l^a_{i,t}(\zeta)\right) + 1) \mathrm{d}\zeta. \end{aligned} \tag{4.10}$$

We assume that the premium $p_{i,t}$ is fixed at $t = 0$ and does not vary with respect to time, $p_{i,t} = p_i$, and neither do inhabited square meters, so $m_{i,t} = m_i$. We can compute the highest premium that homeowners are willing to pay by restricting condition in eq. (4.10) to the equality, obtaining:

$$\begin{aligned} &\pi_c(0) \cdot \log \frac{(RC+1)}{(RC-p_i+1)}+ \\ +\int \pi_c(\zeta) \log &\frac{(RC-l_{i,t}^a(\zeta)+1)}{(RC-p_i-l_{i,t}^a(\zeta)+x\left(l_{i,t}^a(\zeta)\right)+1)} \mathrm{d}\zeta=0. \end{aligned} \tag{4.11}$$

This equality states that the individual is indifferent to the decision to purchase the policy or not, and allows us to derive the risk-based maximum premium p_i^H that the individual is willing to pay per structural typology and municipality.

4.3 Public-private partnership

We now consider the supply side, where the insurer and the government cooperate in risk management. As previously discussed, the goal of the business is maximizing social well-being, while financially protecting the insurer. Therefore, the government forces insurers to apply the lowest possible premiums, given both the demand and the solvency constraints, and offers its support to the business by partially subsidizing reserves and committing to pay reimbursements whenever the reserve is not sufficient for claim compensation.

As the demand can be represented through the maximum premium that individuals are willing to pay, supply is concerned about the constitution of reserves in order to cope with possible future claims. At the beginning of the activity, say $t=0$, the insurer should create a reserve W, that will be increased every year by annual premiums p_i collected from the N_i individuals. Since the government supports the insurers, the reserve is partially subsidized by public capitals. Assume for simplicity that all the premiums are paid at the beginning of the year, while claims are paid when experienced. Hence, a minimum capital requirement W_d should be fixed, so that the government will have to pay W_d in $t=0$ and to refill the fund at the end of the year t if W_t goes below this threshold. So, at the beginning (b) of the year $t=0$ the initial reserve W_0^b is created:

$$W_0^b = W_d + \sum_{i=1}^{N_i} p_i m_i, \tag{4.12}$$

and at the end (e) of the year it will be decreased of the total amount of reimbursement paid during the year:

$$W_0^e = W_0^b - \sum_{i=1}^{N_i} x_{i,0} m_i. \tag{4.13}$$

Since claims $x\left(l^a_{i,t}(\zeta)\right)$ may incur at any random time t and more events may happen close in time, the minimum capital requirement W_d is necessary to guarantee money availability for reimbursement with a sufficiently high probability. Thus, if $W_0^e < W_d$ the government will refill it with an additional amount $W_r = W_d - W_0^e$.

At any subsequent time t, the fund value at the beginning of the year is:

$$W_t^b = W_{t-1} + \sum_{i=1}^{N_i} p_i m_i \qquad \text{with} \qquad W_{t-1} = \max(W_{t-1}^e; W_d), \tag{4.14}$$

while at the end it will be:

$$W_t^e = W_t^b - \sum_{i=1}^{N_i} x_{i,t} m_i. \tag{4.15}$$

However, the insurer is legally asked to meet some solvency constraint and hence need the government to set W_d such that the probability of not being able to promptly pay the claims (“insolvency” probability) below a certain low value ϵ_1.

Let us assume that a negative event hits any building within a municipality. We assume that every policy can generate at most one claim per year and per individual; since reconstructing or restoring a building requires long time, this hypothesis is reasonable. Moreover, assume that actual square meter losses $l^a_{i,t}$ are equal for all the individuals within the same municipality and so does $x_{i,t}$. Consider the N_c municipalities in Italy and indicate the total number of inhabited squared meters in the municipality c as M_c, we have:

$$M_c = \sum_{i \in c} m_i, \qquad \sum_{i \in c} x_{i,t} m_i = X_{c,t} M_c, \tag{4.16}$$

hence

$$X_{c,t} = \frac{\sum_{i \in c} x_{i,t} m_i}{M_c}, \tag{4.17}$$

so we can compute the total amount of claims as:

$$Y_t = \sum_{i=1}^{N_i} x_{i,t} m_i = \sum_{c=1}^{N_c} \sum_{i \in c} x_{i,t} m_i = \sum_{c=1}^{N_c} X_{c,t} M_c. \tag{4.18}$$

Since our policy covers at most one claim per year and per individual, claim occurrence per year and per municipality can be modelled as a Bernoulli random variable $\bar{X}_{c,t} \sim Ber(q_c)$ Olivieri and Pitacco (2010)

$$\bar{X}_{c,t} = \begin{cases} 1 & \text{with probability } q_c, \\ 0 & \text{with probability } 1 - q_c. \end{cases} \tag{4.19}$$

with $q_c = \pi_c\left(\zeta > \zeta_D\right)$ and ζ_D such that $l^a_{i,t}(\zeta_D) = D$.

We can rewrite Y_t as:

$$\begin{aligned} Y_t = & \sum_{c=1}^{N_c} X_{c,t} M_c = \sum_{c=1}^{N_c} M_c \bar{X}_{c,t} x\left(l^a_{c,t,j}\right) = \\ & = \sum_{c=1}^{N_c} \bar{X}_{c,t} \sum_j M_{j,c} x\left(l^a_{c,t,j}\right) = \sum_{c=1}^{N_c} \bar{X}_{c,t} a_{c,t}, \end{aligned} \tag{4.20}$$

where j indicates the structural typology and $M_{j,c}$ is the number of squared meters of properties of type j in municipality c.

A main issue related to covering natural disasters is the high level of correlation between individual risks, which makes the description of the probability distribution of Y_t non-trivial. There is no physical bound for energy propagation and this means that we cannot consider municipalities as perfectly independent among each other, especially in the earthquakes' case. By the way, natural phenomena hit neighbor cities, but far enough municipalities fairly never experience the same event. Therefore, it could be found a certain distance r such that municipalities whose centroids are at least r km far are independent. This assumption is similar to the Hoeffding (1963)'s definition of $(r-1)$-dependence, and allows us to follow his work to model the national claim amount Y_t.

We sample municipalities in N_g groups Y^g of independent units, namely we create the groups in such a way that all the municipalities within a group are at least r km apart from each other. The number n_g of municipalities in group g varies.

The total amount of claims in Italy can thus be obtained as:

$$Y_t = Y_t^1 + Y_t^2 + Y_t^3 + \cdots + Y_t^{N_g}, \tag{4.21}$$

with

$$Y_t^g = \sum_{c \in g} \bar{X}_{c,t} a_{c,t}, \qquad c = 1, \ldots, n_g. \tag{4.22}$$

Each group claim amount Y_t^g is the sum of n_g independent and bounded random variables.

Assuming that the hazard distribution does not vary with respect to time too, expected losses do not depend on t, and neither do $E\left[Y_t\right]$ and $E\left[Y_t^g\right]$. Considering that $\int_0^{\zeta_D} \pi_c(\zeta) x \left[l_{j,c}^a(\zeta)\right] \mathrm{d}\zeta = 0$, the g-th group expected value:

$$\begin{aligned} E\left[Y_t^g\right] = E\left[Y^g\right] = \sum_{c \in g} \sum_j M_{j,c} \int_0^{\infty} \pi_c(\zeta) x \left[l_{j,c}^a(\zeta)\right] \mathrm{d}\zeta = \\ = \sum_{c \in g} \sum_j M_{j,c} \cdot E\left[x\left(l_{j,c}^a\right)\right]. \end{aligned} \tag{4.23}$$

The expected total amount of claims in Italy is:

$$E\left[Y_t\right] = E\left[Y\right] = \sum_{g=1}^{N_g} E\left[Y^g\right]. \tag{4.24}$$

Now we can define the insolvency probability at time t, and impose an upper bound ϵ_1 on it:

$$Prob\left\{ W_{t-1} + \sum_{i=1}^{N_i} p_i m_i - Y_t < 0 \right\} < \epsilon_1, \tag{4.25}$$

or equivalently:

$$Prob\left\{ Y_t > W_{t-1} + \sum_{i=1}^{N_i} p_i m_i \right\} < \epsilon_1. \tag{4.26}$$

We consider the worst case scenario $W_{t-1} = W_d$:

$$Prob\left\{ Y_t > W_d + \sum_{i=1}^{N_i} p_i m_i \right\} < \epsilon_1. \tag{4.27}$$

The minimum capital requirement W_d that the government should guarantee is then obtained by applying the Hoeffding (1963) bound to our weighted sum of independent and bounded random variables:

$$Prob\left\{Y_t > N_c\phi + E\left[Y\right]\right\} < \sum_{g=1}^{N_g} w_g e^{-h_1\phi} E\left[e^{\frac{h_1}{n_g}(Y_t^g - E[Y^g])}\right], \qquad h_1 > 0, \tag{4.28}$$

with $w_g = \frac{n_g}{N_c}$.

Set

$$W_d + \sum_{i=1}^{N_i} p_i m_i = N_c\phi + E\left[Y\right], \tag{4.29}$$

and fix the right hand side of eq. (4.28) equal to ϵ_1:

$$\begin{aligned}
\epsilon_1 &= \sum_{g=1}^{N_g} w_g e^{-h_1\phi} E\left[e^{\frac{h_1}{n_g}(Y_t^g - E[Y^g])}\right] = \\
&= e^{-h_1\phi} \sum_{g=1}^{N_g} w_g E\left[e^{\frac{h_1}{n_g} Y_t^g} e^{-\frac{h_1}{n_g} E[Y^g]}\right] = \\
&= e^{-h_1\phi} \sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g} E[Y^g]} E\left[e^{\frac{h_1}{n_g} Y_t^g}\right] = \\
&= e^{-h_1\phi} \sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g} E[Y^g]} E\left[e^{\frac{h_1}{n_g} \sum_{c\in g} \bar{X}_{c,t} a_{c,t}}\right].
\end{aligned} \tag{4.30}$$

The last expected value in eq. (4.30) is the moment generating function of the sum of random variables $\mathcal{M}_{Y_t^g}\left(\frac{h_1}{n_g}\right)$:

$$E\left[e^{\frac{h_1}{n_g} \sum_{c\in g} \bar{X}_{c,t} a_{c,t}}\right] = \prod_{c\in g} \mathcal{M}_{Y_t^g}\left(\frac{h_1}{n_g}\right) = \prod_{c\in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}}\left(\frac{h_1}{n_g}\right), \tag{4.31}$$

hence eq. (4.30) can be rewritten as:

$$\epsilon_1 = e^{-h_1\phi} \sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g} E[Y^g]} \prod_{c\in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}}\left(\frac{h_1}{n_g}\right). \tag{4.32}$$

Solving eq. (4.32) we obtain ϕ as:

$$\phi = \frac{1}{h_1} \log\left(\frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g} E[Y^g]} \prod_{c\in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}}\left(\frac{h_1}{n_g}\right)}{\epsilon_1}\right) \tag{4.33}$$

and estimate W_d from eq. (4.29):

$$W_d = N_c\phi + E\left[Y\right] - \sum_{i=1}^{N_i} p_i m_i. \tag{4.34}$$

Eq. (4.34) may result in a negative value of W_d, but we bind possible solutions to

$$W_d^* \geq 0. \tag{4.35}$$

In case of $W_d < 0$, we assume that the government will decide to set it equal to 0 and keep an insolvency probability even lower than the desired level: $\epsilon_1^* \leq \epsilon_1$.

Moreover, it is reasonable to suppose that the government aims to minimize the probability to refill the fund with additional capital $W_r = W_d - W_t^e$, so it will need to set a premium sufficiently high to guarantee a low probability bounded from above by ϵ_2 to pay that quantity at any time t:

$$Prob\left\{ W_d - W_t^e > 0 \right\} = Prob\left\{ W_d - W_{t-1} - \sum_{i=1}^{N_i} p_i m_i + Y_t > 0 \right\} < \epsilon_2. \tag{4.36}$$

Once again, consider the worst case scenario $W_{t-1} = W_d$:

$$Prob\left\{ W_d - W_d - \sum_{i=1}^{N_i} p_i m_i + Y_t > 0 \right\} = Prob\left\{ Y_t - \sum_{i=1}^{N_i} p_i m_i > 0 \right\} < \epsilon_2, \tag{4.37}$$

or equivalently:

$$Prob\left\{ Y_t > \sum_{i=1}^{N_i} p_i m_i \right\} < \epsilon_2. \tag{4.38}$$

Note that this condition applies a new constraint on the premiums' value.

Given a sufficiently low probability ϵ_2, we can define the minimum amount of total premiums by applying again the Hoeffding (1963) inequality:

$$Prob\left\{ Y_t > N_c\gamma + E\left[Y\right] \right\} < e^{-h_2\gamma} \sum_{g=1}^{N_g} w_g e^{-\frac{h_2}{n_g} E[Y^g]} \prod_{c \in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}} \left(\frac{h_2}{n_g} \right), \tag{4.39}$$

where $h_2 > 0$. Set

$$\epsilon_2 = e^{-h_2\gamma} \sum_{g=1}^{N_g} w_g e^{-\frac{h_2}{n_g} E[Y^g]} \prod_{c\in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}} \left(\frac{h_2}{n_g} \right) \tag{4.40}$$

and get

$$\gamma = \frac{1}{h_2} \log \left(\frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_2}{n_g} E[Y^g]} \prod_{c\in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}} \left(\frac{h_2}{n_g} \right)}{\epsilon_2} \right) \tag{4.41}$$

which in turn allows us to estimate the minimum allowable value of the sum of premiums $\sum_{i=1}^{N_i} p_i^G m_i$:

$$\sum_{i=1}^{N_i} p_i^G m_i = N_c \gamma + E\left[Y\right]. \tag{4.42}$$

4.4 Insurance model

The maximum value p_i^H that each individual is willing to pay in eq. (4.11) and the minimum amount of total premium necessary to avoid excessive government risk-exposure $\sum_{i=1}^{N_i} p_i^G m_i$ in eq. (4.42) are the two constraints that the supply faces when defining a national insurance scheme. The two equations pose conditions on rates and they may either identify a range of possible values or fail to find a unique solution. However, since we are focused on a publicly supported insurance scheme, it is reasonable to assume that the government will keep the premium as low as possible in order not to financially over-stress homeowners, though this may imply a higher probability of found refill at each t, thus a greater risk for public resources. Therefore, given the desired probability ϵ_2 of government non-financial over-stress we define the optimal premium level p_i^* as:

$$p_i^* = \min(c, 1) \cdot p_i^H \qquad \text{with} \qquad c = \frac{\sum_{i=1}^{N_i} p_i^G m_i}{\sum_{i=1}^{N_i} p_i^H m_i}. \tag{4.43}$$

Premiums as defined in eq. (4.43) are risk-based on municipality hazard and individual structural typology, thus guaranteeing social fairness.

Moreover, the equation implies that:

$$\begin{aligned}\sum_{i=1}^{N_i} p_i^* m_i = \min(c,1)\sum_{i=1}^{N_i} p_i^H m_i = \min\left(1,\frac{1}{c}\right)\sum_{i=1}^{N_i} p_i^G m_i = \\ = \min\left(1,\frac{1}{c}\right)\left(N_c\gamma + E\left[Y\right]\right) = N_c\gamma^* + E\left[Y\right],\end{aligned} \tag{4.44}$$

thus γ^* is

$$\gamma^* = \frac{\min\left(1,\frac{1}{c}\right)\left(E\left[Y\right]+N_c\gamma\right)E\left[Y\right]}{N_c} \leq \gamma \tag{4.45}$$

and the insurer is thus able to guarantee an upper bound ϵ_2^* on the probability to refill the fund equal to:

$$\epsilon_2^* = \frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_2}{n_g}E[Y^g]}\prod_{c\in g}\mathcal{M}_{\bar{X}_{c,t}a_{c,t}}\left(\frac{h_2}{n_g}\right)}{e^{h_2\gamma^*}} \geq \epsilon_2. \tag{4.46}$$

Given the desired upper bound on insolvency probability ϵ_1, the optimal capital minimum requirement W_d^* is then obtained from condition (4.34):

$$W_d^* = \max\left\{N_c\phi + E\left[Y\right] - \sum_{i=1}^{N_i} p_i^* m_i; 0\right\} = N_c\phi^* + E\left[Y\right] - \sum_{i=1}^{N_i} p_i^* m_i, \tag{4.47}$$

with

$$\phi^* = \frac{W_d^* + \sum_{i=1}^{N_i} p_i^* m_i - E\left[Y\right]}{N_c} \geq \phi. \tag{4.48}$$

Thus, the optimal value ϵ_1^* is:

$$\epsilon_1^* = \frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g}E[Y^g]}\prod_{c\in g}\mathcal{M}_{\bar{X}_{c,t}a_{c,t}}\left(\frac{h_1}{n_g}\right)}{e^{h_1\phi^*}}. \tag{4.49}$$

Since ϵ_1 decreases as ϕ increases, the optimal insolvency probability will be at most equal to the level desired by the insurer: $\epsilon_1^* \leq \epsilon_1$.

Moreover, note that:

$$\begin{aligned}W_d^* = N_c\phi^* + E\left[Y\right] - \sum_{i=1}^{N_i} p_i^* m_i = N_c\phi^* + E\left[Y\right] - E\left[Y\right] - N_c\gamma^* = \\ = N_c\left(\phi^* - \gamma^*\right).\end{aligned} \tag{4.50}$$

From eq. (4.46) and (4.49), γ^* and ϕ^* can be defined as:

$$\gamma^* = \frac{1}{h_2} \log \left(\frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_2}{n_g} E[Y^g]} \prod_{c \in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}} \left(\frac{h_2}{n_g} \right)}{\epsilon_2^*} \right) \tag{4.51}$$

and

$$\phi^* = \frac{1}{h_1} \log \left(\frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g} E[Y^g]} \prod_{c \in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}} \left(\frac{h_1}{n_g} \right)}{\epsilon_1^*} \right). \tag{4.52}$$

Given the condition in eq. (4.35), eq. (4.50) implies

$$\frac{\left(\sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g} E[Y^g]} \prod_{c \in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}} \left(\frac{h_1}{n_g} \right) \right)^{\frac{1}{h_1}}}{\left(\sum_{g=1}^{N_g} w_g e^{-\frac{h_2}{n_g} E[Y^g]} \prod_{c \in g} \mathcal{M}_{\bar{X}_{c,t} a_{c,t}} \left(\frac{h_2}{n_g} \right) \right)^{\frac{1}{h_2}}} \cdot \frac{(\epsilon_2^*)^{\frac{1}{h_2}}}{(\epsilon_1^*)^{\frac{1}{h_1}}} \geq 1. \tag{4.53}$$

In particular, if a parameter $h = h_1 = h_2$ is chosen, eq. (4.50) becomes

$$W_d^* = \frac{N_c}{h} \log \left(\frac{\epsilon_2^*}{\epsilon_1^*} \right). \tag{4.54}$$

Eq. (4.54) shows that the amount of public resources needed increases with the ratio $\epsilon_2^*/\epsilon_1^*$, and more importantly, eq. (4.53) collapses to:

$$\epsilon_2^* \geq \epsilon_1^*, \tag{4.55}$$

indicating that insolvency should never be preferred to the disbursement of public funds, thus enforcing the government role of social guarantor. The minimum W_d^* value corresponds to $\epsilon_1^* = \epsilon_2^*$ and is equal to 0.

However, $\epsilon_2^*/\epsilon_1^*$ affects W_d^* logarithmically, while the capital requirement is largely determined by N_c/h. Therefore, W_d^* is directly proportional to the number of municipalities, and inversely related to the parameter h, whose value is determined by the government's initial preferences ϵ_1 and ϵ_2 and the overall risk distribution.

4.5 Application

4.5.1 Individuals' willingness to pay for seismic policies.

Premium model application to the seismic case requires particular attention due to the hazard component $\zeta = PGA$. We can estimate $\pi(\zeta)$ as $\pi(PGA) = |\frac{\mathrm{d}\lambda(PGA)}{\mathrm{d}(GPA)}|$. The absence of seismic movements $\zeta = 0$ corresponds to the case of no seismic event happening in the year, thus we have $l_{i,t}(0) = 0$ and $x\left(l_{i,t}(\zeta)\right) = 0$. This allows us to include the case of no seismic event in the integral term of condition (4.11):

$$\int_0^{\infty} \pi_c(PGA) \log \frac{\left(RC - l^a_{i,t}(PGA) + 1\right)}{\left(RC - p_{i,t} - l^a_{i,t}(PGA) + x\left(l^a_{i,t}(PGA)\right) + 1\right)} \mathrm{d}(PGA) = \\ = 0. \tag{4.56}$$

In Section 3.3.1 we have shown that $\lambda_c(PGA)$ approximately behaves as a Power Law distribution and therefore we have:

$$\pi_c(PGA) = \left| \frac{d(\lambda(PGA))}{d(PGA)} \right| = \alpha_c PGA^{-\beta_c}, \tag{4.57}$$

whose domain does not include values in $[0, PGA_{min_c}[$, with

$$PGA_{min_c} = e^{\frac{\log\left(\frac{\alpha_c}{\beta_c - 1}\right)}{\beta_c - 1}}. \tag{4.58}$$

This implies that, in this case, the integral in condition (4.56) cannot be evaluated in $[0, +\infty[$ but in $[PGA_{min_c}, +\infty[$ only. However, PGA_{min_c} take values ranging from $7.92e^{-09}$ to 0.002, and are small enough to include the case of no seismic loss.

The loss function per structural typology $l^a_{j,t}(PGA)$ is derived from eq. (3.2):

$$l^a_{j,t}(PGA) = \frac{1}{K_j} \sum_{k=1}^{K_j} \sum_{LS=1}^{N_k} RC(LS) \cdot \left[P_k\left(LS|PGA\right) - P_k\left(LS + 1|PGA\right)\right], \tag{4.59}$$

with $P_k\left(N_{LS_k} + 1|PGA\right) = 0$.

Condition (4.11) for seismic risk becomes:

$$\int_{PGA_{min_c}}^{\infty} \alpha_c PGA^{-\beta_c} \log\left(\frac{RC - l^a_{i,t}(PGA) + 1}{RC - p_{i,t} - l^a_{i,t}(PGA) + x\left(l^a_{i,t}(PGA)\right) + 1}\right) \mathrm{d}(PGA) = 0. \tag{4.60}$$

4.5.2 Individuals' willingness to pay for flood policies.

The premium model application to flood is simpler with respect to the seismic. Here, hazard is represented by depth $\zeta = \delta$ and $l_{i,t}(\delta)$ is obtained by the depth-percent damage curve $g_j(\delta)$ for the number of storeys j. The probabilistic component $\pi_c(\zeta)$ is given by $f(N_F)$ defined in equation (3.8), whose estimation has been discussed in Section 3.4.1. We define the individual flooding probability from equation (3.14) as:

$$P(N_F \geq 1) = (1 - f^{A_P}_{N_F}(0)) \cdot ext_{c,P3} \cdot \frac{\bar{c}^f}{N_c^{AP}}. \tag{4.61}$$

The probability of no flood events in a year $\pi_c(0)$ is then defined as:

$$f_{N_F}(0) = \left[1 - (1 - f^{A_P}_{N_F}(0)) \cdot ext_{c,P3} \cdot \frac{\bar{c}^f}{N_c^{AP}}\right] := \pi_c(0); \tag{4.62}$$

while $\pi_c(\delta)$ corresponds to:

$$\pi_c(\delta) = (1 - f^{A_P}_{N_F}(0)) \cdot ext_{c,P3} \cdot \frac{\bar{c}^f}{N_c^{AP}} \cdot f_{\delta|N_F}(\delta | N_F \geq 1) \tag{4.63}$$

So condition (4.11) becomes:

$$\begin{gathered}\left[1 - (1 - f^{A_P}_{N_F}(0)) \cdot ext_{c,P3} \cdot \frac{\bar{c}^f}{N_c^{AP}}\right] \cdot \log\left(\frac{RC + 1}{RC - p_{i,t} + 1}\right) + \\ +(1 - f^{A_P}_{N_F}(0)) \cdot ext_{c,P3} \cdot \frac{\bar{c}^f}{N_c^{AP}} \cdot \int_0^{\infty} f_{\delta|N_F}(\delta | N_F \geq 1) \cdot \\ \cdot \log\left(\frac{RC - \frac{RC}{100} g_j(\delta) + 1}{RC - p_{i,t} - \frac{RC}{100} \cdot g_j(\delta) + x\left[\frac{RC}{100} \cdot g_j(\delta)\right] + 1}\right) \mathrm{d}\delta = 0.\end{gathered} \tag{4.64}$$

We focus on the integral in the second term, and split it into two components:

$$\begin{aligned} &\int_0^\infty f_{\delta|N_F}(\delta|N_F \geq 1)\cdot \\ &\cdot \log\left(\frac{RC - \frac{RC}{100}\cdot g_j(\delta)+1}{RC - p_{i,t} - \frac{RC}{100}\cdot g_j(\delta) + x\left[\frac{RC}{100}\cdot g_j(\delta)\right]+1}\right)\mathrm{d}\delta = \\ &= \int_0^\infty f_{\delta|N_F}(\delta|N_F \geq 1)\cdot \log\left(RC - \frac{RC}{100}\cdot g_j(\delta)+1\right)\mathrm{d}\delta + \\ &-\int_0^\infty f_{\delta|N_F}(\delta|N_F \geq 1)\cdot \\ &\cdot \log\left(RC - p_{i,t} - \frac{RC}{100}\cdot g_j(\delta) + x\left[\frac{RC}{100}\cdot g_j(\delta)\right]+1\right)\mathrm{d}\delta, \end{aligned} \tag{4.65}$$

then, we consider them separately.

Since g_j is a positive non-decreasing function that becomes constant at level 100% corresponding to a certain depth δ_{max}, the first integral can be simplified to:

$$\begin{aligned} &\int_0^\infty f_{\delta|N_F}(\delta|N_F \geq 1)\cdot \log\left(RC - \frac{RC}{100}\cdot g_j(\delta)+1\right)\mathrm{d}\delta = \\ &= \int_0^{\delta_{max}} f_{\delta|N_F}(\delta|N_F \geq 1)\cdot \log\left(RC - \frac{RC}{100}\cdot g_j(\delta)+1\right)\mathrm{d}\delta + \\ &+ \int_{\delta_{max}}^\infty f_{\delta|N_F}(\delta|N_F \geq 1)\cdot \log(1)\,\mathrm{d}\delta = \\ &= \int_0^{\delta_{max}} f_{\delta|N_F}(\delta|N_F \geq 1)\cdot \log\left(RC - \frac{RC}{100}\cdot g_j(\delta)+1\right)\mathrm{d}\delta. \end{aligned} \tag{4.66}$$

The second integral involves two piecewise functions: $g_j(\delta)$ and $x\left(g_j(\delta)\right)$. Defining δ_D such that $g_j(\delta_D)\cdot\frac{RC}{100} = D$ and δ_E such that $g_j(\delta_E)\cdot\frac{RC}{100} = E + D$ and considering δ_{max}, we can split it into 4 components:

$$
\begin{aligned}
&\int_0^{\infty} f_{\delta|N_F}(\delta|N_F \geq 1) \cdot \\
&\qquad \cdot \log\left(RC - p_{i,t} - \frac{RC}{100} \cdot g_j(\delta) + x\left[\frac{RC}{100} \cdot g_j(\delta)\right] + 1\right) \mathrm{d}\delta = \\
&= \int_0^{\delta_D} f_{\delta|N_F}(\delta|N_F \geq 1) \cdot \log\left(RC - p_{i,t} - \frac{RC}{100} \cdot g_j(\delta) + 1\right) \mathrm{d}\delta + \\
&+ \log\left(RC - p_{i,t} - D + 1\right) \cdot \left[F_{\delta|N_F}(\delta_E|N_F \geq 1) - F_{\delta|N_F}(\delta_D|N_F \geq 1)\right] + \\
&+ \int_{\delta_E}^{\delta_{max}} f_{\delta|N_F}(\delta|N_F \geq 1) \cdot \log\left(RC - p_{i,t} - \frac{RC}{100} \cdot g_j(\delta) + E + 1\right) \mathrm{d}\delta + \\
&\qquad + \log\left(E - p_{i,t} + 1\right)\left[1 - F_{\delta|N_F}(\delta_{max}|N_F \geq 1)\right]. \qquad (4.67)
\end{aligned}
$$

Summing up, insured purchasing indifference condition (4.11) for the flood case study is:

$$
\begin{aligned}
&\left[1 - (1 - f_{N_F}^{A_P}(0)) \cdot ext_{c,P3} \cdot \bar{c}^f\right] \cdot \log\left(\frac{RC + 1}{RC - p_{i,t} + 1}\right) + \\
&\qquad + (1 - f_{N_F}^{A_P}(0)) \cdot ext_{c,P3} \cdot \bar{c}^f \cdot \\
&\cdot \left\{ \int_0^{\delta_{max}} f_{\delta|N_F}(\delta|N_F \geq 1) \cdot \log\left(RC - \frac{RC}{100} \cdot g_j(\delta) + 1\right) \mathrm{d}\delta + \right. \\
&- \int_0^{\delta_D} f_{\delta|N_F}(\delta|N_F \geq 1) \cdot \log\left(RC - p_{i,t} - \frac{RC}{100} \cdot g_j(\delta) + 1\right) \mathrm{d}\delta + \\
&- \log\left(RC - p_{i,t} - D + 1\right) \cdot \left[F_{\delta|N_F}(\delta_E|N_F \geq 1) - F_{\delta|N_F}(\delta_D|N_F \geq 1)\right] + \\
&- \int_{\delta_E}^{\delta_{max}} f_{\delta|N_F}(\delta|N_F \geq 1) \cdot \log\left(RC - p_{i,t} - \frac{RC}{100} \cdot g_j(\delta) + E + 1\right) \mathrm{d}\delta + \\
&\qquad \left. - \log\left(E - p_{i,t} + 1\right)\left[1 - F_{\delta|N_F}(\delta_{max}|N_F \geq 1)\right] \right\} = 0. \qquad (4.68)
\end{aligned}
$$

4.5.3 Aggregate claim distribution

In order to apply the model, $\mathcal{M}_{\bar{X}_{c,t} a_{c,t}}\left(\frac{h}{n_g}\right)$ should be defined and perhaps some distributional assumption should be introduced. The best distributional form depends on the scope of the coverage, and the analysis might rather compare multiple significant scenarios represented by alternative distributional hypotheses.

An informative choice is focusing on the expected value of claims, and thus assuming that Y_t is a weighted sum of Bernoulli random variables. Assuming that the properties within a municipality are perfectly correlated, Y_t equal to:

$$\begin{aligned}
Y_t = \sum_{c=1}^{N_c} X_{c,t} M_c = \sum_{c=1}^{N_c} M_c \bar{X}_{c,t} \int_{\zeta_D}^{\infty} \pi_c\left(\zeta | \zeta > \zeta_D\right) x\left[l_{c,t}^a\left(\zeta\right)\right] \mathrm{d}\zeta = \\
= \sum_{c=1}^{N_c} \bar{X}_{c,t} \sum_j M_{j,c} \int_{\zeta_D}^{\infty} \pi_c\left(\zeta | \zeta > \zeta_D\right) x\left[l_{j,c,t}^a\left(\zeta\right)\right] \mathrm{d}\zeta = \sum_{c=1}^{N_c} \bar{X}_{c,t} a_c.
\end{aligned} \tag{4.69}$$

Note that now parameters a_c do not depend on time t and are constants. The expected reimbursement of the g-th group $E\left[Y_t^g\right]$ in eq. (4.23) therefore becomes

$$\begin{aligned}
E\left[Y_t^g\right] = \sum_{c \in g} q_c a_c = \\
= \sum_{c \in g} \pi\left(\zeta > \zeta_D\right) \sum_j M_{j,c} \int_{\zeta_D}^{\infty} \pi_c\left(\zeta | \zeta > \zeta_D\right) x\left[l_{j,c,t}^a\left(\zeta\right)\right] \mathrm{d}\zeta = \\
= \sum_{c \in g} \pi\left(\zeta > \zeta_D\right) \sum_j M_{j,c} \int_{\zeta_D}^{\infty} \frac{\pi_c\left(\zeta\right)}{\pi_c\left(\zeta > \zeta_D\right)} x\left[l_{j,c,t}^a\left(\zeta\right)\right] \mathrm{d}\zeta = \\
= \sum_{c \in g} \sum_j M_{j,c} \int_{\zeta_D}^{\infty} \pi_c\left(\zeta\right) x\left[l_{j,c,t}^a\left(\zeta\right)\right] \mathrm{d}\zeta = \sum_{c \in g} \sum_j M_{j,c} E\left[x\left(l_{j,c,t}^a\right)\right],
\end{aligned} \tag{4.70}$$

and the moment generating function of $\bar{X}_{c,t} a_c$ can be written through the probability generating function of a weighted sum of Bernoulli variables:

$$\mathcal{M}_{\bar{X}_{c,t} a_c}\left(\frac{h}{n_g}\right) = \mathcal{G}_{\bar{X}_{c,t} a_c}\left(e^{\frac{h}{n_g}}\right) = \left[1 + \left(e^{\frac{h}{n_g} a_c} - 1\right) q_c\right]. \tag{4.71}$$

However, since Bernoulli variables are bounded in $[0, 1]$, each Y_t^g is bounded between $0 \leq Y_t^g \leq \sum_{c \in g} a_c = b_g$. In the seismic model,

$$a_c^s = \sum_k x_{k,c}^s \tag{4.72}$$

with

$$x^s_{k,c} = \int_{PGA_{min_c}}^{\infty} x \Bigg(\frac{1}{M_k} \sum_{j=1}^{M_k} \sum_{LS=1}^{N_k} RC(LS) \cdot$$

$$\cdot \left[P_j\left(LS|PGA\right) - P_j\left(LS+1|PGA\right)\right] \cdot \left| \frac{\mathrm{d}\lambda_c\left(PGA\right)}{\mathrm{d}(PGA)} \right| \Bigg) \mathrm{d}(PGA), \quad (4.73)$$

while expected claims for flood policies are

$$a^f_c = \sum_j x^f_{j,c} \quad (4.74)$$

with

$$\begin{aligned} x^f_{j,c} &= x \left(\int_0^{\infty} \frac{RC}{100} \cdot P(N_F \geq 1) \cdot g_j(\delta) f_{\delta|N_F}(\delta|N_F \geq 1)\mathrm{d}\delta \right) = \\ &= P(N_F \geq 1) \cdot x \left(\int_0^{\infty} \frac{RC}{100} \cdot g_j(\delta) f_{\delta|N_F}(\delta|N_F \geq 1)\mathrm{d}\delta \right) = \\ &= P(N_F \geq 1) \cdot \Bigg(\int_{\delta_D}^{\delta_E} \frac{RC}{100} \cdot g_j(\delta) f_{\delta|N_F}(\delta|N_F \geq 1)\mathrm{d}\delta + \\ &\qquad + \int_{\delta_E}^{\infty} E \cdot f_{\delta|N_F}(\delta|N_F \geq 1)\mathrm{d}\delta \Bigg) = \\ &= P(N_F \geq 1) \cdot \Bigg(\int_{\delta_D}^{\delta_E} \frac{RC}{100} \cdot g_j(\delta) f_{\delta|N_F}(\delta|N_F \geq 1)\mathrm{d}\delta + \\ &\qquad + E \cdot \lambda_{\delta|N_F}(\delta_E|N_F \geq 1) \Bigg). \end{aligned} \quad (4.75)$$

According to Hoeffding (1963), the bounds in eq. (4.28) and (4.39) simplify for the case of bounded weighted random variables. Consider, for instance, the bound as in eq. (4.28)

$$Prob\left\{ Y_t > N_c\phi + E\left[Y\right] \right\} < \sum_{g=1}^{N_g} w_g e^{-h_1\phi} E\left[e^{\frac{h_1}{n_g}(Y^g_t - E[Y^g])} \right], \qquad h_1 > 0.$$

According to Lemma 1 in Hoeffding (1963), since the final term in the right-hand side of the inequality is convex, we know that:

$$E\left[e^{\frac{h_1}{n_g}(Y_t^g - E[Y^g])}\right] \leq e^{\frac{h_1}{n_g}E[Y_t^g]}\left[\frac{b_g - E\left[Y^g\right]}{b_g} + \frac{E\left[Y^g\right]}{b_g}e^{\frac{h_1}{n_g}b_g}\right] =$$
$$= e^{\frac{h_1}{n_g}E[Y^g]}\left[1 + \frac{E\left[Y^g\right]}{b_g}\left(e^{\frac{h_1}{n_g}b_g} - 1\right)\right] = e^{L(h_g)}. \quad (4.76)$$

$L(h_g)$ can be specified as

$$L(h_g) = -h_g p_g + \ln\left(1 + p_g\left(e^{h_g} - 1\right)\right) \quad (4.77)$$

with

$$h_g = \frac{h_1}{n_g}b_g \qquad \text{and} \qquad p_g = \frac{E\left[Y^g\right]}{b_g}.$$

According to the proof of Theorem 2 in Hoeffding (1963),

$$L(h_g) \leq \frac{1}{8}h_g^2 = \frac{1}{8}\left(\frac{h_1 b_g}{n_g}\right)^2, \quad (4.78)$$

hence the bound can be rewritten as

$$Prob\left\{Y_t > N_c\phi + E\left[Y\right]\right\} < \sum_{g=1}^{N_g} w_g e^{-h_1\phi}\left(e^{\frac{1}{8}\left(\frac{h_1 b_g}{n_g}\right)^2}\right) =$$
$$= \sum_{g=1}^{N_g} w_g e^{-h_1\phi + \frac{1}{8}\left(\frac{h_1 b_g}{n_g}\right)^2}. \quad (4.79)$$

In order to get the best possible upper bound, we find the minimum of the right-hand side of the inequality as a function of ϕ, thus obtaining

$$h_1 = \frac{4\phi n_g^2}{b_g^2}. \quad (4.80)$$

Substituting the parameter h_1 as defined in eq.(4.80) into eq.(4.79), the Hoeffding's bound simplifies to

$$Prob\left\{Y_t > N_c\phi + E\left[Y\right]\right\} < \sum_{g=1}^{N_g} w_g e^{-\frac{2\phi^2 n_g^2}{b_g^2}}. \quad (4.81)$$

Similarly, the bound in eq.(4.39) can be rewritten as

$$Prob\left\{Y_t > N_c\gamma + E\left[Y\right]\right\} < \sum_{g=1}^{N_g} w_g e^{-\frac{2\gamma^2 n_g^2}{b_g^2}}. \quad (4.82)$$

4.5.4 Insurance Model

We now revise the insurance model by applying the distributional assumptions in Section 4.5.3.

Once again, parameters ϕ and γ are obtained by fixing the desired probabilities ϵ_1 and ϵ_2 equal to the right-hand side of inequalities (4.81) and (4.82) respectively.

Premiums p_i^H are obtained as in Section 4.5.1 and 4.5.2, and p_i^G are computed as in eq. (4.42). The optimal premium amount $\sum_{i=1}^{N_i} p_i^* m_i$ is again computed according to eq. (4.43).

While ϕ^* and γ^* remain unchanged as in eq. (4.52) and (4.51),

$$\epsilon_1^* = \sum_{g=1}^{N_g} w_g e^{-\frac{2{\phi^*}^2 n_g^2}{b_g^2}} \tag{4.83}$$

and

$$\epsilon_2^* = \sum_{g=1}^{N_g} w_g e^{-\frac{2{\gamma^*}^2 n_g^2}{b_g^2}} . \tag{4.84}$$

Optimal values ϕ^* and γ^* here cannot be expressed as explicit functions of ϵ_1^* and ϵ_2^* respectively, hence eq. (4.50)

$$W_d^* = N_c \left(\phi^* - \gamma^*\right) \geq 0$$

cannot be directly related to the two probabilities. However, the equation implies $\phi^* \geq \gamma^*$ and since ϵ_1^* and ϵ_2^* are inversely related to ϕ^* and γ^* respectively, the condition is satisfied if and only if

$$\epsilon_2^* \geq \epsilon_1^*. \tag{4.85}$$

Similar to the special case $h = h_1 = h_2$, the model indicates that providing additional public resources should always be preferred to being insolvent. Coherently, $W_d^* = 0$ is obtained if and only if $\epsilon_1^* = \epsilon_2^*$. Of course, the fund is again directly proportional to the number of municipalities N_c. Initial preferences ϵ_1 and ϵ_2 and claim distribution are now reflected by ϕ^* and γ^* instead.

4.6 Results

The insurance model has been applied to the Italian residential building stock according to the assumption discussed in Section 4.5. Results

Table 12: Public-private insurance scheme for earthquake risk management.

		$\epsilon_1 = 0.01, \epsilon_2 = 0.02$				
Deductible	Excess of loss (per square meter)	$\sum_{i=1}^{N_i} p_i^*$ (Mln)	c	W_d^* (Mln)	ϵ_1^*	ϵ_2^*
0	1500	10735.784 (0.000)	1.394 (0.021)	7970.726 (0.080)	0.010 (0.000)	0.061 (0.035)
0	1200	9725.082 (0.000)	1.505 (0.021)	8563.810 (0.073)	0.010 (0.000)	0.080 (0.030)
200	1500	8837.312 (0.000)	1.576 (0.021)	8582.130 (0.068)	0.010 (0.000)	0.095 (0.027)
200	1200	8221.215 (0.000)	1.652 (0.021)	8771.088 (0.065)	0.010 (0.000)	0.112 (0.024)

Note: results are based on 100 samplings over the $N_c = 6404$ municipalities for which data were fully available. Policies are defined on deductible and excess of loss and listed by row, while columns represent the model's relevant variables. Reported values are mean and coefficient of variation.

here presented refer to initial preferences $\epsilon_1 = 0.01$ and $\epsilon_2 = 0.02$. The former value is representative of solvency requirement in Solvency II, the latter has been fixed slightly greater than ϵ_1 according to the model description. In addition, we assumed $r = 50$ km, thus adopting a precautionary hypothesis on spatial correlation. This criterion allows for multiple sampling solutions, each resulting in different optimal values of the relevant variables. Therefore, final results have been averaged over 100 samplings.

Four policies have been considered, differing on the level of deductible (none or 200) and maximum coverage (none or 1200 per square meter). Note that deductible equal to 0 corresponds to the absence of it, while maximum coverage equal to 1500 per square meter indicates that no maximum coverage applies.

Results for seismic policies are reported in Table 12, where relevant variables are presented in terms of their mean and coefficient of variation (CoV). It can be noticed that the optimal premiums always corresponds to the maximum price that individuals are willing to pay, p_i^H, as shown by (i) $c \geq 1$; (ii) the coefficient of variation of $\sum_{i=1}^{N_i} p_i^*$ equal to 0; and (iii) $\epsilon_1^* = \epsilon_1$. When interpreting these findings, there are two elements that should be carefully evaluated: individuals' risk aversion and spatial correlation.

On one hand, because of risk aversion, individuals are keen to buy

Table 13: Optimal seismic premiums per square meter.

Deductible		0	0	200	200
Excess of loss (per square meter)		1500	1200	1500	1200
RC.gl	min	0.460	0.460	0.034	0.034
	mean	6.620	6.582	4.413	4.106
	max	32.261	32.261	30.471	30.471
RC.sl	min	0.034	0.034	0.007	0.007
	mean	2.005	1.676	1.351	1.350
	max	10.226	10.226	8.922	8.683
A.gl	min	0.027	0.027	0.008	0.008
	mean	1.902	1.712	1.536	1.424
	max	10.200	10.197	9.269	9.124
A.sl	min	0.012	0.012	0.011	0.011
	mean	1.745	1.535	1.278	1.205
	max	10.153	10.153	7.810	7.696
M	min	0.075	0.062	0.041	0.041
	mean	4.461	3.910	3.975	3.544
	max	50.182	40.042	31.387	30.926

Note: the Table shows the minimum, average and maximum premium at the municipal level per each combination of structural typology (row) and coverage limits (columns).

policies at a premium greater than their expected loss; the more individuals are risk averse, the higher is the amount of premium that the insurer is able to collect and, in turn, the lower is the additional capital needed to satisfy the solvency constraint ϵ_1. On the other hand, spatial correlation between individual risks inflate loss volatility and bumps the tail of the aggregate loss distribution, thereby increasing the amount of capital corresponding to ϵ_1. Parameter $c > 1$ indicates that individual's risk aversion is not sufficient to tackle the risk-enhancing effect of spatial correlation at the aggregate level.

As a consequence of $c > 1$, the premium p_i^G that would satisfy the desired solvency constraint ϵ_1 and capital re-investment probability ϵ_2 does not meet market demand, and would generate a market failure. This result suggests a potential weakness of the free market: since the government has easier access to capital markets than private companies, it is reasonable to assume that a private insurer will require a probability

Table 14: Public-private insurance scheme for flood risk management.

		$\epsilon_1 = 0.01, \epsilon_2 = 0.02$				
Deductible	Excess of loss (per square meter)	$\sum_{i=1}^{N_i} p_i^*$ (Mln)	c	W_d^* (Mln)	ϵ_1^*	ϵ_2^*
0	1500	1021.072 (0.000)	5.644 (0.035)	7422.276 (0.041)	0.010 (0.000)	0.408 (0.029)
0	1200	823.444 (0.000)	6.957 (0.035)	7567.733 (0.040)	0.010 (0.000)	0.534 (0.028)
200	1500	1020.885 (0.000)	5.607 (0.035)	7366.177 (0.041)	0.010 (0.000)	0.402 (0.029)
200	1200	823.257 (0.000)	6.898 (0.035)	7496.555 (0.040)	0.010 (0.000)	0.547 (0.027)

Note: results are based on 100 samplings on $N_c = 7772$ municipalities for which data were fully available. Policies are defined on deductible and excess of loss and listed by row, while columns represent the model's relevant variables. Reported values are mean and coefficient of variation.

of capital re-investment at most equal to the one desired by the government; under this condition, p_i^G would be the minimum pure[2] premium that traditional insurers would be able to charge to the homeowner, and the policy would not be purchased. The result is even more significant if we consider that the premiums p_i^H are estimated under assumptions of rather favorable risk attitude of the population. In fact, empirical evidence often suggests low risk-aversion of the homeowners, mainly due to information asymmetries (Kunreuther and Pauly, 2004). Therefore, the optimal premiums p_i^* identified here should be looked at as upper bounds and the public-private insurance can set these rates only if citizens have been properly informed and educated towards risks, or if a mandatory insurance requirement has been introduced. Whatever the real degree of risk aversion, it appears evident that the private sector cannot meet the demand properly and achieve high penetration rates for the whole national territory. This is perfectly consistent with the current Italian situation: as reported by Cesari and D' Aurizio (2019) [3], only 0.8% of the housing stock is insured against earthquakes and insured homes are largely located in areas at medium-low seismic risk.

Limiting coverage might help the insurer controlling risk's volatility, thus allowing for lower premiums. In particular, being earthquakes

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[2] Without profit load and expenses.

[3] See pp. 42.

Table 15: Optimal seismic premiums per square meter.

Deductible		0	0	200	200
Maximum coverage (per square meter)		1500	1200	1500	1200
	min	2e-06	1e-06	2e-06	1e-06
1 storey	mean	1.355	1.088	1.355	1.088
	max	16.140	12.962	16.139	12.961
	min	1e-16	1e-16	1e-16	1e-16
2 storeys	mean	0.198	0.161	0.198	0.161
	max	2.382	1.933	2.381	1.933
	min	1e-16	1e-16	1e-16	1e-16
3 or more storeys	mean	0.182	0.147	0.182	0.147
	max	2.188	1.771	2.187	1.770

Note: the Table shows the minimum, average and maximum premium at the municipal level per each combination of structural typology (row) and coverage limits (columns).

low frequency-high intensity perils, the aggregate loss distribution is strongly affected by rare events causing severe damages and therefore we expect maximum coverage to reduce the insurer's financial exposure more than deductibles. In Table 12 we can clearly notice that increasing coverage limits reduces the overall minimum amount of reserves that should be guaranteed at the beginning of each year $W_{min} = \sum_{i=1}^{N_i} p_i^* + W_d^*$, but the minimum capital requirement W_d^* increases and ϵ_2^* deviates more and more from the desired level. As confirmed by the greater values of c, individuals are in fact reluctant to deductibles and maximum coverage due to increasing risk aversion[4]. Coverage limits negatively affect individual willingness to pay, that in turn lower their contribution to reserves and the insurer is left with an enhanced financial pressure. As said, limits-reluctance is here generated by risk-aversion, but unfortunately $c > 1$ even for full-coverage policies, thus suggesting the need for a government intervention on the private market.

Results for floods are collected in Table 14. Once again $c > 1$ and the need for a government intervention in the insurance private market is even more strongly suggested (higher value of c). However, deductibles are here beneficial to the insurer and, in fact, both W_d^* and ϵ_2^* are lower when $D = 200$ applies. Though findings are completely different from

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[4] Risk aversion has been here represented by means of the utility function $u(x) = \log(x) + 1$, whose relative risk aversion coefficient is increasing in x.

the seismic case study, this evidence still generates due to a combination of risk aversion and loss distribution. Being high frequency-low intensity perils, floods mostly cause small claims on relatively low return periods and the aggregate loss distribution therefore concentrates on low values. On the other side, increasing risk aversion makes individuals extremely averse to high losses and less concerned about low damages that can afford by them own: in Table 15, when applying the deductible $D = 200$, p_i^H remains substantially unchanged. Combining the two effects, deductibles relieve the insurer commitment while not substantially modifying individual's willingness to pay.

By contrast, introducing a maximum coverage worsens the insurer condition by increasing both ϵ_2^* and W_d^*. This effect is clear when comparing the policy $(D = 0, E = 1500)$ with the $(D = 0, E = 1200)$ or $(D = 200, E = 1500)$ with $(D = 200, E = 1200)$. This limit in fact diminishes the risk of the insurer by lowering the tail of its aggregate loss distribution but leaves highest level of individual risk to property-owners. Because of increasing risk aversion, the premium individuals are willing to pay is therefore much lowered, and the amount of public funds needed much increased.

The most interesting result is obtained when comparing policies with estimated losses in Section 3.5: though earthquakes produce expected losses that are more than seven times greater than those from floods, the minimum capital requirement W_d^* for the two hazards almost coincide. Once again, the shape of the aggregate loss distribution and individual's increasing risk aversion jointly determine this surprising result. As low frequency-high intensity perils, earthquakes sometimes produce enormous damages that individuals are extremely concerned about. Therefore, owners are willing to pay a premium consistently higher than their expected loss. On the other side, floods happen quite more often but their damages are usually minor and can mostly be afforded by homeowners themselves. People are risk averse, and hence keen to buy a policy and get rid of their flood risk, but the amount they are willing to pay for the insurance protection is lower. In other words, both the two premiums are higher than the corresponding expected loss but the difference between the premium that the homeowner pays for the earthquake policy and its expected seismic loss is greater than that of floods:

$$p_i^{H,s} - E(L_i^s) > p_i^{H,f} - E(L_i^f). \tag{4.86}$$

The higher is the difference between premiums and expected losses, the lower is the additional capital needed by the insurance in order to manage the risk, and hence the lower is the capital requirement W_d^*. This becomes clear when considering the ratio $\frac{\sum_{i=1}^{N_i} p_i^*}{W_d^*}$. Ratios for seismic policies span between 0.93 and 1.34 and indicate that the government and the homeowners almost equally contribute to the constitution of reserves. On the other side, flood risk is much unfairly distributed between the two agents with ratios $[0.11, 0.14]$.

Evidence suggests that spatial correlation strongly affects the development of the private insurance market for both the two perils, but larger values of ϵ_2^* indicate that flood risk is even more difficult to insure. A second level risk transfer (such as a reinsurance contract or a catastrophe linked securities) might help reducing ϵ_2 by lowering the aggregate loss tail.

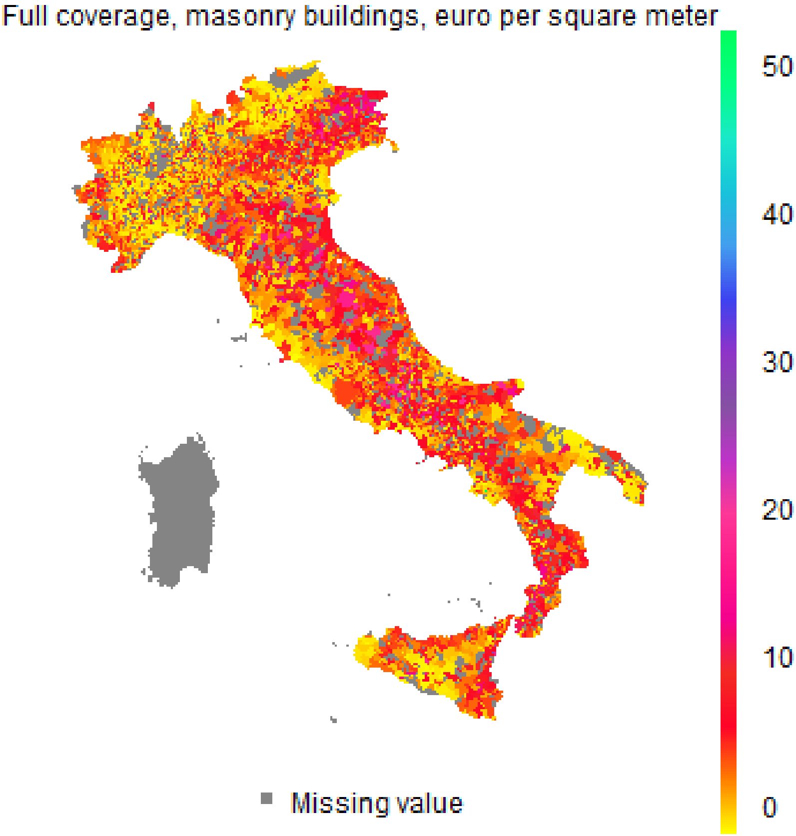
To conclude, Figures 13 and 14 show annual optimal premiums per square meter p_i^H for the most vulnerable structural typology per each municipality for the two perils respectively. Since premiums are risk-based, the two maps reflect the hazard component of risk modeling and hence report a pattern similar to the maps on loss per square meter in Figure 6 and 8.

4.7 Conclusion

In order to cope with the effects of natural risks, a public-private insurance scheme has been proposed. Our insurance model is intended to alleviate the financial burden that natural events place on governments, while at the same time assisting individuals and protecting the insurance business. Therefore, in our model, property-owners, an insurer and the government co-operate in risk financing. Though expected losses generated by floods and earthquakes are considerably different, we found that the amount of public funds needed to manage the two perils is almost the same. We argue that this evidence is generated by a combination of individuals' increasing risk aversion and hazard loss distributions.

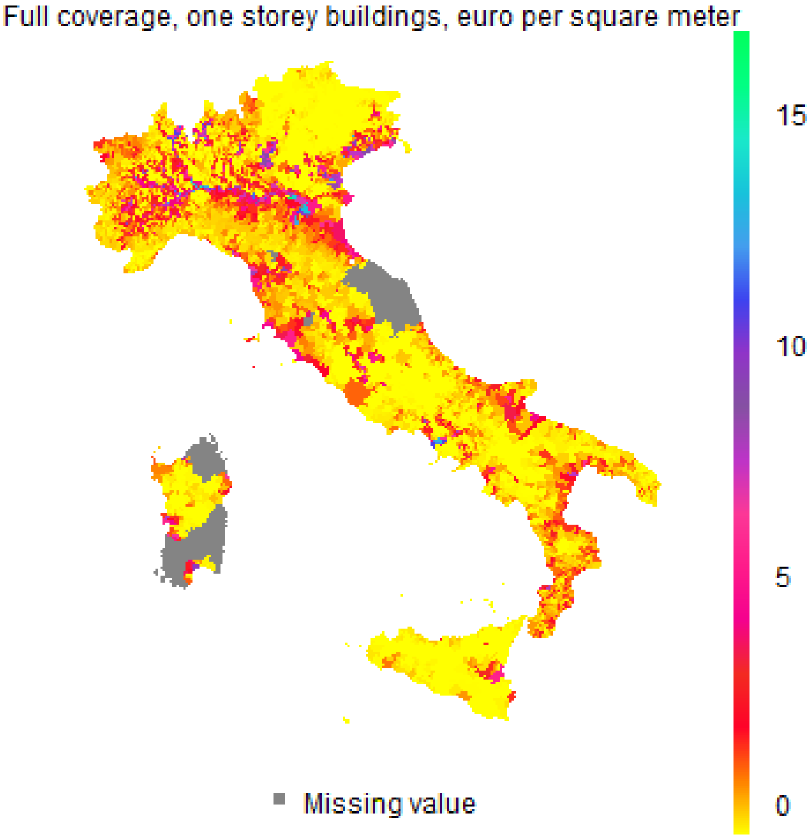
Unfortunately, our results show that neither policy is sustainable by the private market alone: due to spatial correlation among insured assets, the maximum premiums that individuals are willing to pay do not meet the insurer's solvency or capital constraints for any policy considered. Without the financial support of the government, a private insurer would be forced to drive up premiums, which would not meet the demand and would therefore not be purchased.

Figure 13: Optimal premiums per square meter for earthquake policies on masonry buildings.



Note: the map refers to the full coverage ($D = 0, E = 1500$ per square meter) policy, that has been estimated over $N_c = 6404$. The minimum value reported is 0.075 and therefore yellow municipalities should be interpreted as approximately 0. The maximum premium is 50.182.

Figure 14: Optimal premiums per square meter for flood policies on one-storey buildings.



Note: the map refers to the full coverage policy ($D = 0$,$E = 1500$ per square meter), that has been estimated over $N_c = 7772$.

Chapter 5

Insuring multiple hazards

This Chapter is a joint work with my supervisors Giorgio Stefano Gnecco and Fabio Pammolli. The full text of the article is also available from the arXiv repository, preprint number 2006.05840.

Abstract

As well known in finance, merging portfolios is beneficial if risks are uncorrelated, as floods and earthquakes are likely to be. Here we extend the model defined in the previous chapter to the multi-hazard scenario. Our analysis shows that the hypothetical Italian public-private insurer can benefit from risk differentiation by jointly managing earthquake and flood risks through a multi-hazard policy: the amount of public capital needed is lower than what would be necessary if the two risks were managed separately. Another desirable feature emerges: rates for multi-hazard policies are more geographically homogeneous, and therefore promote fairness perception among the population. However, it emerged that under no circumstances does the maximum premium that individuals are willing to pay match the desired insurer's capital constraints.

5.1 Introduction

In the previous chapter a public-private insurance model has been created for single peril policies. As well known in finance, merging portfolios of different risks is beneficial if risks are uncorrelated, as floods and earthquakes are likely to be. It remains to be seen whether benefits from risk diversification counteract the negative impact of spatial correlation emerged in previous results. This chapter goes through what has been discussed so far and extends the analysis to multi-hazard.

The first section is devoted to risk assessment, and therefore comes back to the risk-modeling introduced in Chapter 3. While assessing single hazard risk is challenging, studying possible consequences from several perils is even more complicated. Kappes et al. (2012) identifies two major issues raising in a multi-hazard context: finding a common measure suitable to describing all the hazards considered, and understanding the relationship linking them. Regarding the former issue, since it is impossible to find a geological or atmospheric indicator describing both flood and earthquakes, the two risk have been here assessed separately and compared in monetary terms only. The second point refers to the correlation between the two phenomena. Based on some empirical evidence in the literature, we argue that the two risks are uncorrelated.

To our knowledge, Marzocchi et al. (2012) is the only work addressing multi-hazard risk assessment in Italy by studying seismic, volcanic, hydrogeological, flooding, landslide and industrial risk in the municipality of Casalnuovo. However, this analysis is restricted to a municipality and has been applied therein to human and societal risk only and does not pursue any insurance decision. A different framework is therefore needed for our case study.

The following section extends the insurance model in Chapter 4 to multi-hazard. The model is shaped by redefining supply and demand. In particular, we show that the maximum premium that individuals are willing to pay is equal to the sum of the premiums for the two single hazard policies, while the required amount of public capital is less than or equal to the sum necessary when managing the risk separately.

The last section presents results, which clearly show that benefit from risk diversification are not sufficient to override the effect of spatial correlation. However, additional positive externalities emerge: for example, premiums for multi-hazard policies are geographically more homogeneous with respect to the single hazard's, thus favoring the perception of fair-treatment among the population.

5.2 Risk assessment

As discussed in Chapter 3, four elements determine losses from natural events : H, E, V and L. A mathematical model for loss estimation should therefore be able to capture the relevant characteristics of each component and describe those process that link them. Since every natural phenomenon has specific characteristics, studying the effects of multiple hazards furthermore complicates risk assessment.

In particular, in our two-peril framework, H should encompass both floods and earthquakes and therefore a common physical measure able to describe both the two perils should be identified. However, given the different characteristics of the two perils, this is impossible, and we can compare the two risks in money-value only. As a consequence, we are forced to assess the two risks separately, though this approach cannot capture the potential dependence among them.

In our multi-hazard risk assessment, we refer to two hazard-indicators ζ^s and ζ^f, where apexes s and f indicate seismic and flood risks, respectively. Each indicator is associated to a certain probability of occurrence $F^s(\zeta^s)$ and $F^f(\zeta^f)$. Hence, hazard is described by both ζ^h and $F^h(\zeta^h)$. As we have previously shown, vulnerability functions are defined over a specific hazard-indicator, and their output can be easily converted into monetary terms. Referring to the definition of loss in Sections 3.3.4 and 3.4.4, for simplicity we convey L and V in a unique function $v^h(\zeta^h)$, with $h = s, f$. Expected losses per square meter generated by a peril can hence be estimated as

$$l^h = F^h(\zeta^h)v^h(\zeta^h)E^h, \qquad h = s, f. \tag{5.1}$$

As anticipated, multi-hazard expected loss might be affected by potential interactions of the two perils, and therefore we need some assumption on the degree of dependence between floods and earthquakes. Unfortunately, our database do not offer any information about if and how the two perils interact, but some empirical analysis in the literature (Tarvainen, Jarva, and Greiving, 2006; Cesari and D' Aurizio, 2019) support the hypothesis of independence between seismic and flood risks. However, various degrees of independence are also possible. Following the work of Brunette et al. (2015), we now discuss two possible independence scenarios. First, we consider the hazards to be mutually exclusive, thus assuming that floods and earthquakes cannot happen simultaneously and the structure can get damaged by one peril only; we will refer to this case as "mutual exclusion scenario". As an alternative, we consider perils to be "mutually independent", allowing them to potentially happen together. In this case, the property may be damaged by at least one of the two events.

- **Mutual exclusion scenario**
  If the two hazards are mutually exclusive the joint probability of an event F_{dep}^{MH} is obtained by simply summing the single hazard probabilities
  $$F_{exc}^{MH} = F^s(\zeta^s) + F^f(\zeta^f), \tag{5.2}$$
  and we can compute expected losses per square meter as:
  $$l_{exc}^{MH} = F^s(\zeta^s)v^s(\zeta^s) + F^f(\zeta^f)v^f(\zeta^f). \tag{5.3}$$
  We can notice that in case of mutually exclusion the multi-hazard loss per square meter coincides with the sum of the single hazards expected losses:
  $$l_{exc}^{MH} = l^s + l^f. \tag{5.4}$$

- **Mutual independence scenario**
  Avoid now any dependence and allow the hazards to happen simultaneously. The joint occurrence probability F_{ind}^{MH} becomes:
  $$F_{ind}^{MH} = F^s(\zeta^s) + F^f(\zeta^f) - F^s(\zeta^s)F^f(\zeta^f). \tag{5.5}$$
  Expected losses now arise from flood, earthquakes, or a combination of the two. When the two events happen together the damages suffered by the property are defined by a new vulnerability function $v^{s+f}(\zeta^s, \zeta^f)$, therefore expected losses per square meter are obtained as:
  $$\begin{aligned} l_{ind}^{MH} = & \left[F^s(\zeta^s) - F^s(\zeta^s)F^f(\zeta^f)\right] v^s(\zeta^s) + \\ & + \left[F^f(\zeta^f) - F^s(\zeta^s)F^f(\zeta^f)\right] v^f(\zeta^f) + \\ & + F^s(\zeta^s)F^f(\zeta^f)v^{s+f}(\zeta^s, \zeta^f) = \\ & = F^s(\zeta^s)v^s(\zeta^s) + F^f(\zeta^f)v^f(\zeta^f) + \\ & + F^s(\zeta^s)F^f(\zeta^f)\left[v^{s+f}(\zeta^s, \zeta^f) - v^s(\zeta^s) - v^f(\zeta^f)\right] = \\ & = l^s + l^f + F^s(\zeta^s)F^f(\zeta^f)\left[v^{s+f}(\zeta^s, \zeta^f) - v^s(\zeta^s) - v^f(\zeta^f)\right]. \end{aligned} \tag{5.6}$$

We can notice that $l_{ind}^{MH} > l_{exc}^{MH}$ if $v^{s+f}(\zeta^s, \zeta^f) > v^s(\zeta^s) + v^f(\zeta^f)$ and this happens when the interaction of the two events amplifies the damages they cause on the property. We are unable to define the function $v^{s+f}(\zeta^s, \zeta^f)$ or to state whether it is smaller or greater than the sum of the two single hazard vulnerability functions. However, the low number of reported events suggests that the associated probability $F^s(\zeta^s)F^f(\zeta^f)$ is reasonably close to 0. Moreover, assuming the expected multi-hazard loss l_{ind}^{MH} equal to l_{exc}^{MH} is a prudential assumption if $v^{s+f}(\zeta^s, \zeta^f) < v^s(\zeta^s) + v^f(\zeta^f)$ because it requires the insurer to create slightly greater funds, thus effectively getting the probability of insolvency and fund-refill lower than the required level. For these reasons, we estimate expected losses as:

$$l_{ind}^{MH} = l^s + l^f. \tag{5.7}$$

5.3 Homeowner's purchase decision

In Chapter 4 we have argued that premiums should meet the demand and that maximum rates that individuals are willing to pay pose a constraint to an insurance model. Similar to the single-hazard policy, the demand constraint in a multi-hazard framework is therefore given by the equality:

$$u_{\text{not insured}}^{MH} = u_{\text{insured}}^{MH}. \tag{5.8}$$

Given the assumption of independence between floods and earthquakes and the individual utility functions defined in Chapter 4, we can now address the multi-hazard purchase decision problem. We refer to seismic events by means of the apex s and flood by f, and for simplicity individual loss $l_{i,t}$ are indicated by $l_{i,t}^s$ for earthquakes and $l_{i,t}^f$ for floods. In addition, single hazard and multi-hazard policies are specified by means of apexes as SH and MH.

Given the probability of multiple events' probabilities as defined in eq. (5.2) and losses computed as in eq. (5.4), the reimbursement function in eq. (4.1) becomes:

$$x^{MH} = \begin{cases} 0, & \text{with prob. } \pi_c^s(0) + \pi_c^f(0), \\ x^s = x\left(l_{i,t}^s\right), & \text{with prob. } 1 - \pi_c^s(0), \qquad 0 < x\left(l_{i,t}^s\right) \leq l_{i,t}^s, \\ x^f = x\left(l_{i,t}^f\right), & \text{with prob. } 1 - \pi_c^f(0), \qquad 0 < x\left(l_{i,t}^f\right) \leq l_{i,t}^f, \end{cases} \tag{5.9}$$

where $i \in c$ and

$$x^h = x\left(l_{i,t}^h\right) = \begin{cases} 0 & \text{if } l_{i,t}^h \leq D, \\ l_{i,t}^h - D & \text{if } D < l_{i,t}^h < E, \\ E - D & \text{if } l_{i,t}^h \geq E, \end{cases} \qquad h = s, f. \tag{5.10}$$

Hence, individual utilities of being and not being insured in eq. (4.4)-(4.5) for multi-hazard policies are:

$$u_{\text{not insured}}^{MH} = \left[\pi_c^s(0) + \pi_c^f(0)\right] u(RC) + \left[1 - \pi_c^s(0)\right] u(RC - l^s) + \\ + \left[1 - \pi_c^f(0)\right] u(RC - l^f) \tag{5.11}$$

and

$$u_{\text{insured}}^{MH} = \left[\pi_c^s(0) + \pi_c^f(0)\right] u(RC - p^{MH}) + \\ + \left[1 - \pi_c^s(0)\right] u(RC - p^{MH} - l^s + x^s) + \\ + \left[1 - \pi_c^f(0)\right] u(RC - p^{MH} - l^f + x^f). \tag{5.12}$$

In Section 4.2 the maximum premium that an homeowner is willing to pay for a single hazard policy is the quantity p^{SH} solving the equality:

$$u_{\text{not insured}}^{SH} = u_{\text{insured}}^{SH}. \tag{5.13}$$

with

$$u_{\text{not insured}}^{SH} = \pi_c^{SH}(0) u(RC) + \left[1 - \pi_c^{SH}(0)\right] u(RC - l^{SH}) \tag{5.14}$$

and

$$u_{\text{insured}}^{SH} = \pi_c^{SH}(0) u(RC - p^{SH}) + \left[1 - \pi_c^{SH}(0)\right] u(RC - p^{SH} - l^{SH} + x^{SH}), \tag{5.15}$$

for $SH = f, s$.

Comparing MH and SH utilities, we get:

$$u_{\text{insured}}^{MH} = u_{\text{not insured}}^{MH} = u_{\text{not insured}}^{s} + u_{\text{not insured}}^{f} = \\ = u_{\text{insured}}^{s} + u_{\text{insured}}^{f}. \tag{5.16}$$

This equality states that the homeowner utility of buying both the two single hazard policies is equal to the utility of buying a multi-hazard one. However, when evaluating one peril per time, policies prices are fixed by solving a consume decision with two options - to buy or not to buy the policy-, but a multi-hazard framework extends the range of possible choice: the individual may decide to buy a MH policy, both the SH policies, one out of the two SH, or neither of them. We know that if the policy is priced at p^SH the individual is indifferent between buying or not the single-hazard policy, and eq. (5.16) states that the sum of the two utilities equals the utility of buying a MH one. We should then investigate the option of buying both the two single hazard policies $(s+f)$:

$$u^{s+f}_{\text{insured}} \geq u^{s+f}_{\text{not insured}} \tag{5.17}$$

$$\begin{aligned} u^{s+f}_{\text{insured}} = &\left[\pi^s_c(0) + \pi^f_c(0)\right] u(RC - p^s - p^f) + \\ &+ \left[1 - \pi^s_c(0)\right] u(RC - p^s - p^f - l^s + x^s) + \\ &+ \left[1 - \pi^f_c(0)\right] u(RC - p^s - p^f - l^f + x^f) \end{aligned} \tag{5.18}$$

while

$$\begin{aligned} u^{s+f}_{\text{not insured}} = &\left[\pi^s_c(0) + \pi^f_c(0)\right] u(RC) + \\ &+ \left[1 - \pi^s_c(0)\right] u(RC - l^s + x^s) + \\ &+ \left[1 - \pi^f_c(0)\right] u(RC - l^f + x^f). \end{aligned} \tag{5.19}$$

Note that the premium paid by the owner in this scenario is $p^{s+f} = p^s + p^f$. Assuming consumer's perfect rationality and neglecting any operational cost that a policy may generate, the individual prefers a multi-hazard policy to two single-hazard ones if $p^{MH} < p^s + p^f$ because it implies that $u^{MH}_{\text{insured}} > u^{s+f}_{\text{insured}}$. Therefore

$$u^{s+f}_{\text{not insured}} = u^{MH}_{\text{not insured}} = u^s_{\text{not insured}} + u^f_{\text{not insured}}. \tag{5.20}$$

which in turn implies:

$$u^{s+f}_{\text{insured}} = u^{MH}_{\text{insured}} = u^s_{\text{insured}} + u^f_{\text{insured}}. \tag{5.21}$$

Thus, the maximum premium that an individual is willing to pay for a multi-hazard policy makes him indifferent between any purchase choice and is equal to

$$p^{MH,H} = p^s + p^f. \tag{5.22}$$

5.4 Public-private partnership

Main differences in risk-pooling single- or multi- hazard policies are determined by the different loss, reimbursement and premium functions, that are now described by eq. (5.4), (5.9) - (5.10) and (5.22).

We now construct the fund W^{MH} for multi-hazard policies by extending the single-hazard model. The reader can find the extended description of the procedure in Section 4.3.

The multi-hazard fund at the beginning $W_t^{MH,b}$ and at the end $W_t^{MH,e}$ of the year t, are now:

$$W_t^{MH,b} = W_{t-1}^{MH} + \sum_{i=1}^{N_i} p_i^{MH} m_i = W_{t-1}^{MH} + \sum_{i=1}^{N_i} \left(p_i^s + p_i^f\right) m_i \tag{5.23}$$

with

$$W_{t-1}^{MH} = \max(W_{t-1}^{MH,e}; W_d^{MH}), \tag{5.24}$$

and

$$W_t^{MH,e} = W_t^{MH,b} - \sum_{i=1}^{N_i} x_{i,t}^{MH} m_i = W_t^{MH,b} - \sum_{i=1}^{N_i} \left(x_{i,t}^s + x_{i,t}^f\right) m_i. \tag{5.25}$$

Assume that an earthquake or a flood hits any building within a municipality and that every policy can generate at most one claim per hazard per year. Square meter expected losses $l_{i,t}^{MH}$ are equal for all the individuals within the same municipality and so does $x_{i,t}^{MH}$. Given the number of inhabited squared meters $M_c = \sum_{i \in c} m_i$, the total claims value per municipality is:

$$\sum_{i \in c} x_{i,t}^{MH} m_i = \sum_{i \in c} \left(x_{i,t}^s + x_{i,t}^f\right) m_i = \left(X_{c,t}^s + X_{c,t}^f\right) M_c, \tag{5.26}$$

and the total national amount is

$$Y_t^{MH} = \sum_{i=1}^{N_i} x_{i,t}^{MH} m_i = \sum_{c=1}^{N_c} \sum_{i \in c} x_{i,t}^{MH} m_i = \sum_{c=1}^{N_c} \left(X_{c,t}^s + X_{c,t}^f\right) M_c =$$

$$= Y_t^s + Y_t^f, \tag{5.27}$$

and therefore is equal to the sum of the national claims for earthquakes Y_t^s and floods Y_t^f computed by means of eq. (4.18). We model claim probabilities by means of Bernoulli variables $\bar{X}^s_{c,t} \sim Ber(q^s_c)$ and $\bar{X}^f_{c,t} \sim Ber(q^f_c)$ with $q^s_c = \pi^s_c\,(\zeta^s > \zeta_D)$ and $q^f_c = \pi^f_c\,\left(\zeta^f > \zeta_D\right)$ and apply equation (4.20):

$$Y_t^{MH} = \sum_{c=1}^{N_c} \left(\bar{X}^s_{c,t} a^s_{c,t} + \bar{X}^f_{c,t} a^f_{c,t} \right). \tag{5.28}$$

Assuming municipalities that are at least 50 km far each other to be independent, we can recall the sample that have been created for single hazard policies. Considering the two hazards separately, we will have N_g groups of municipalities' seismic risks and other N_g groups for floods. Each group will contain n_g municipalities:

$$Y_t^{s,g} = \sum_{c \in g} \bar{X}^s_{c,t} a^s_{c,t} \qquad c = 1, \ldots, n_g \tag{5.29}$$

$$Y_t^{f,g} = \sum_{c \in g} \bar{X}^f_{c,t} a^f_{c,t} \qquad c = 1, \ldots, n_g \tag{5.30}$$

such that

$$Y_t^{MH} = Y_t^{s,1} + Y_t^{s,2} + \cdots + Y_t^{s,N_g} + Y_t^{f,1} + Y_t^{f,2} + \cdots + Y_t^{f,N_g}. \tag{5.31}$$

Defining $w_g = \frac{n_g}{N_c}$, the expected total amount of claims in Italy is:

$$E\left[Y_t^{MH}\right] = E\left[Y^{MH}\right] = \sum_{g=1}^{N_g} w_g \left(E\left[Y_t^{s,g}\right] + E\left[Y_t^{f,g}\right] \right), \tag{5.32}$$

with $E\left[Y_t^{s,g}\right]$ and $E\left[Y_t^{f,g}\right]$ computed as in (4.23).
Applying the Hoeffding (1963) bound as in eq.(4.27)-(4.34), we get to the definition of both insolvency probability and W_d. We fix the insolvency probability ϵ_1:

$$\begin{aligned} \epsilon_1 = e^{-h_1\phi} \sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g} E\left(Y^{s,g} + Y^{f,g}\right)} E\left[e^{\frac{h_1}{n_g}\left(Y_t^{s,g} + Y_t^{f,g}\right)} \right] = \\ = e^{-h_1\phi} \sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g} E\left(Y^{s,g} + Y^{f,g}\right)} E\left[e^{\frac{h_1}{n_g}\left(Y_t^{s,g}\right)} e^{\frac{h_1}{n_g}\left(Y_t^{f,g}\right)} \right] = \\ = e^{-h_1\phi} \sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g} E\left(Y^{s,g} + Y^{f,g}\right)} E\left[e^{\frac{h_1}{n_g}\left(\bar{X}^s_{c,t} a^s_{c,t}\right)} e^{\frac{h_1}{n_g}\left(\bar{X}^f_{c,t} a^f_{c,t}\right)} \right], \end{aligned} \tag{5.33}$$

and since seismic and flood risk are independent:

$$
\begin{aligned}
\epsilon_1 = e^{-h_1\phi}\sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g}E\left(Y^{s,g}+Y^{f,g}\right)} E\left[e^{\frac{h_1}{n_g}\left(\bar{X}^s_{c,t}a^s_{c,t}\right)}\right] E\left[e^{\frac{h_1}{n_g}\left(\bar{X}^f_{c,t}a^f_{c,t}\right)}\right] = \\
= e^{-h_1\phi}\left(\sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g}\left(E(Y^{s,g})+E\left(Y^{f,g}\right)\right)} \prod_{c\in g}\mathcal{M}_{\bar{X}^s_{c,t}a^s_{c,t}}\left(\frac{h_1}{n_g}\right)\right. \\
\left.\prod_{c\in g}\mathcal{M}_{\bar{X}^f_{c,t}a^f_{c,t}}\left(\frac{h_1}{n_g}\right)\right) = \\
= e^{-h_1\phi}\left(\sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g}\left(E(Y^{s,g})+E\left(Y^{f,g}\right)\right)}\rho\right) \quad (5.34)
\end{aligned}
$$

with

$$
\rho = \prod_{c\in g}\mathcal{M}_{\bar{X}^s_{c,t}a^s_{c,t}}\left(\frac{h_1}{n_g}\right)\mathcal{M}_{\bar{X}^f_{c,t}a^f_{c,t}}\left(\frac{h_1}{n_g}\right). \quad (5.35)
$$

The minimum capital requirement for a multi-hazard public insurance is

$$
W_d^{MH} = N_c\phi + E\left[Y\right] - \sum_{i=1}^{N_i}\left(p_i^s + p_i^f\right)m_i \quad (5.36)
$$

with

$$
\phi = \frac{1}{h_1}\log\left(\frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g}\left(E(Y^{s,g})+E\left(Y^{f,g}\right)\right)}\rho}{\epsilon_1}\right) \quad (5.37)
$$

The probability of fund-refill ϵ_2 and the minimum amount of premiums $\sum_{i=1}^{N_i} p_i^{MH,G} m_i$ that the insurer needs given a certain W_d are obtained by applying the Hoeffding (1963) bound as in (4.36)-(4.42). Hence, fixing

$$
\epsilon_2 = e^{-h_2\gamma}\left(\sum_{g=1}^{N_g} w_g e^{-\frac{h_2}{n_g}\left(E(Y^{s,g})+E\left(Y^{f,g}\right)\right)}\rho\right) \quad (5.38)
$$

we get

$$
\sum_{i=1}^{N_i} p_i^{MH,G} m_i = N_c\gamma + E\left[Y\right] \quad (5.39)
$$

where γ is computed as:

$$\gamma = \frac{1}{h_2} \log \left(\frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_2}{n_g}\left(E(Y^{s,g})+E\left(Y^{f,g}\right)\right)} \rho}{\epsilon_2} \right) \tag{5.40}$$

5.5 Insurance model

The model for the definition of a public-private insurance scheme with multi-hazard policies can be defined as in Section 4.4, therefore here we briefly extend the model to the multi-hazard scenario, but the reader can refer to the previous Section for technical details.

The two fundamental conditions are now defined by equations (5.22) and (5.39). The optimal premium p_i^{*MH} is estimated as:

$$p_i^{MH^*} = \min(c, 1) \cdot p_i^{MH,H} \qquad \text{with} \qquad c = \frac{\sum_{i=1}^{N_i} p_i^{MH,G} m_i}{\sum_{i=1}^{N_i} p^{MH,H} m_i}, \tag{5.41}$$

from which we obtain

$$\sum_{i=1}^{N_i} p_i^{MH^*} m_i = \min\left(c, \frac{1}{c}\right) N_c \gamma + E\left[Y\right] = N_c \gamma^* + E\left[Y\right], \tag{5.42}$$

and the optimal probability of fund-refill ϵ_2^*:

$$\epsilon_2^* = \frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_2}{n_g}\left(E(Y^{s,g})+E\left(Y^{f,g}\right)\right)} \rho}{e^{h_2 \gamma^*}}, \tag{5.43}$$

where γ^* is

$$\gamma^* = \frac{\min\left(1, \frac{1}{c}\right) \left(E\left[Y\right] - N_c \gamma\right) - E\left[Y\right]}{N_c}. \tag{5.44}$$

The optimal $W_d^{MH^*}$ is estimated as in equation (4.47):

$$\begin{aligned} W_d^{MH^*} &= \max \left\{ N_c \phi + E\left[Y\right] - \sum_{i=1}^{N_i} p_i^{MH^*} m_i ; 0 \right\} = \\ &= N_c \phi^* + E\left[Y\right] - \sum_{i=1}^{N_i} p_i^{MH^*} m_i = N_c \left(\phi^* - \gamma^*\right), \end{aligned} \tag{5.45}$$

with

$$\phi^* = \frac{W_d^* + \sum_{i=1}^{N_i} p_i^{MH^*} m_i - E\left[Y\right]}{N_c}, \tag{5.46}$$

and the optimal value ϵ_1^* is:

$$\epsilon_1^* = \frac{\sum_{g=1}^{N_g} w_g e^{-\frac{h_1}{n_g}\left(E(Y^{s,g})+E\left(Y^{f,g}\right)\right)}\rho}{e^{h_1\gamma^*}}. \tag{5.47}$$

As in the single-hazard scenario, some distributional assumptions are needed in order to solve the model. We keep the assumptions as in Section 4.5.3, and therefore we represent Y_t as a weighted sum of Bernoulli random variables. We assume that the properties within a municipality are perfectly correlated. Hence, the Hoeffding (1963) bound simplifies and the probabilities ϵ_1^* and ϵ_2^* become:

$$\epsilon_1^* = \sum_{g=1}^{N_g} w_g e^{-\frac{2{\phi^*}^2 n_g^2}{b_g^2}} \tag{5.48}$$

and

$$\epsilon_2^* = \sum_{g=1}^{N_g} w_g e^{-\frac{2{\gamma^*}^2 n_g^2}{b_g^2}}, \tag{5.49}$$

where

$$b_g^2 = \sum_{c\in g} a_c^s + a_c^f. \tag{5.50}$$

5.6 Results

For multi-hazard analysis, only municipalities where both seismic and flood data are available have been considered, thereby restricting the database to $N_c = 6217$.

As in Section 4.6, municipalities have been assumed independent if centroids are at least 50 km far and 100 samplings have been considered for final results. The four policies considered for single hazard policies have also been estimated for multi-hazard: (i) a full coverage policy ($D = 0$, $E = 1500$); (ii) one with a maximum coverage equal to 1200 per square meter ($D = 0$, $E = 1200$); (iii) one with a deductible equal to 200 ($D = 200$, $E = 1500$); (iv) a policy with both the maximum coverage and the deductible ($D = 200$, $E = 1200$). Initial preferences have been again fixed to $\epsilon_1 = 0.01$ and $\epsilon_2 = 0.02$.

Results are presented in Table 16 together with the corresponding single hazard policies, that have been re-estimated on the restricted number of municipalities for the sake of comparability. As expected, seismic risk dominates the multi-hazard scenario because of the consistently higher impact on the national territory. In particular, since

$$\sum_{i=1}^{N_i} p_i^{MH*} = \sum_{i=1}^{N_i} p_i^{s*} + \sum_{i=1}^{N_i} p_i^{f*}, \tag{5.51}$$

we can notice that multi-hazard premiums amount $\sum_{i=1}^{N_i} p_i^*$ is mostly determined by seismic risk and just a small portion of it is due to floods. Though premiums for the two single hazard policies are extremely different, the corresponding minimum capital requirement W_d^* is similar (see Section 4.6), and for the multi-hazard policy

$$W_d^{MH*} \leq W_d^{s*} + W_d^{f*}. \tag{5.52}$$

Therefore, multi-hazard policies need for less public capital than managing the two hazards separately, and this finding is attributable to risk differentiation.

However, advantages from multi-hazard are evident with respect to flood risk, but a bit controversial when we look at the seismic risk. The multi-hazard parameter c is a bit greater than that of the seismic case and much smaller than in the flood case but, unfortunately, is always $c \leq 1$. Our analysis suggests that benefits from risk differentiation are not sufficient for the natural risks to be entirely managed by the private market and once again, a government intervention is highly recommended. This evidence is confirmed by the probability ϵ_2^*, that shows a behavior similar to c and is always greater than the desired level, and $\epsilon_1^* = \epsilon_1$. Moreover, public-private insurances typically transfer the highest layers of risk to a public reinsurer or through a State guarantee, and this further helps limiting the insurer's losses while keeping premiums low. In a fully private environment the cost of reinsurance is always higher, further exacerbating the difficulties of the private market to fulfill both the solvency requirement and policyholder's willingness to pay (Paudel, Botzen, and Aerts, 2013; Paudel, Botzen, Aerts, and Dijkstra, 2015).

As far as coverage limits concern, the minimum amount of public funds W_d^* and the minimum probability ϵ_2^* are obtained with the full coverage policy, while applying a deductible $D = 200$ or a maximum coverage $E = 1200$ lead to similar results. In any case, the worst solution would be applying the two limits together, since both the greatest W_d^* and the highest ϵ_2^* are here obtained.

In addition to benefits from risk differentiation, a government may prefer multi-hazard policies for another interesting feature: risk-based premiums are much more geographically uniform than those of single hazards. In fact, Figure 15 mapping premiums for the most vulnerable buildings (masonry-one storey) shows a quite homogeneous price at the municipal level, while differences are a bit more emphasized in the corresponding single hazard (see Figures 13 and 14). From the public sector perspective, a uniform rating system is desirable because it weakens the perception of unequal treatment between the property-owners from different areas and therefore allows easier acceptance by the population. On the other hand, different risk-based premiums signal the riskiness of the area to its inhabitants and is therefore important to discourage the construction of most vulnerable housing structures and to encourage preventive behavior. The current rating also preserves this desirable feature since premiums are defined on structural typologies among which rates substantially vary (see Table 17).

5.7 Conclusion

Our analysis shows that the amount of public capital necessary for insuring earthquakes and floods can be reduced by jointly managing the two risks. Along with this benefit from risk differentiation, multi-hazard policies allow the insurer to apply rates that are more geographically homogeneous, therefore favoring the perception of fair treatment among the population. Unfortunately, our results show that not even multi-hazard policies meet the insurer's solvency or capital constraints. Once again, evidence suggests the need for the government to intervene in the insurance market for natural disasters. However, our results for single-peril and multi-peril policies show that the probability of the government having to inject further capital may be moderate. Though the insurance scheme reduces the government's financial burden due to natural perils with respect to the current state, adding some layer of risk transfer might be beneficial. For example, CatBonds or some level of reinsurance may reduce losses suffered by the government and their volatility.

Table 16: Multi-hazard public-private insurance scheme.

			$\epsilon_1 = 0.01, \epsilon_2 = 0.02$				
Deductible	Excess of loss (per square meter)		$\sum_{i=1}^{N_i} p_i^*$ (Mln)	c	W_d^* (Mln)	ϵ_1^*	ϵ_2^*
0	1500	MH	11185.123	1.694	13281.008	0.010	0.091
			(0.000)	(0.024)	(0.068)	(0.000)	(0.029)
		S	10356.859	1.424	8194.243	0.010	0.063
			(0.000)	(0.022)	(0.080)	(0.000)	(0.035)
		F	828.264	6.346	7359.961	0.010	0.403
			(0.000)	(0.036)	(0.044)	(0.000)	(0.029)
0	1200	MH	10046.430	1.852	13983.445	0.010	0.120
			(0.000)	(0.024)	(0.063)	(0.000)	(0.025)
		S	9378.433	1.537	8760.141	0.010	0.082
			(0.000)	(0.022)	(0.074)	(0.000)	(0.030)
		F	667.997	7.820	7469.278	0.010	0.427
			(0.000)	(0.036)	(0.043)	(0.000)	(0.028)
200	1500	MH	9335.925	1.919	13879.044	0.010	0.132
			(0.000)	(0.024)	(0.061)	(0.000)	(0.024)
		S	8507.814	1.612	8766.645	0.010	0.097
			(0.000)	(0.022)	(0.069)	(0.000)	(0.027)
		F	828.110	6.305	7305.976	0.010	0.396
			(0.000)	(0.036)	(0.044)	(0.000)	(0.029)
200	1200	MH	8575.042	2.047	14183.694	0.010	0.163
			(0.000)	(0.024)	(0.058)	(0.000)	(0.022)
		S	7907.199	1.692	8945.297	0.010	0.114
			(0.000)	(0.022)	(0.066)	(0.000)	(0.024)
		F	667.843	7.756	7401.415	0.010	0.435
			(0.000)	(0.036)	(0.043)	(0.000)	(0.028)

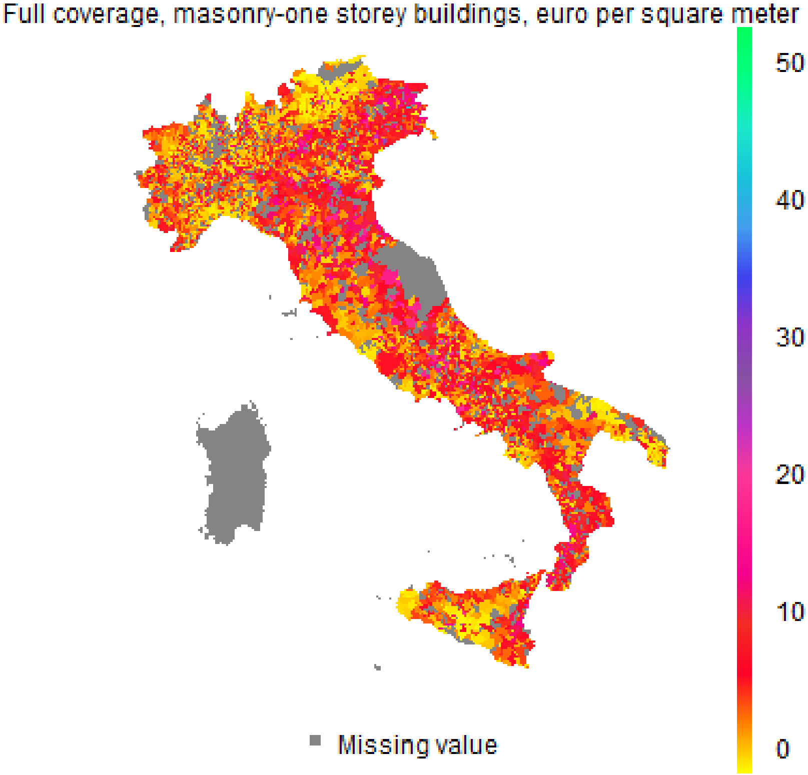
Note: the Table shows multi-hazard (MH), seismic (S) and flood (F) insurance for the Italian residential building stock. Results have been estimated over 100 samplings on $N_c = 6217$ municipalities for which data were fully available for both flood and earthquakes. Policies are defined on deductible and excess of loss and listed by row, while columns represent the model's relevant variables. Reported values are mean and coefficient of variation.

Table 17: Optimal multi-hazard premiums per square meter.

				Deductible					
				0			200		
				1s	2s	3s	1s	2s	3s
Excess of Loss (per square meter)	1500	RC.gl	min	0.644	0.592	0.591	0.051	0.051	0.051
			mean	7.541	6.730	6.719	5.322	4.512	4.500
			max	32.261	32.261	32.261	30.471	30.471	30.471
		RC.sl	min	0.038	0.034	0.034	0.012	0.008	0.008
			mean	2.932	2.122	2.110	2.195	1.384	1.373
			max	16.951	10.679	10.638	16.935	9.277	9.248
		A.gl	min	0.036	0.036	0.036	0.021	0.021	0.021
			mean	2.849	2.038	2.027	2.478	1.667	1.656
			max	19.136	10.793	10.730	19.111	9.625	9.595
		A.sl	min	0.021	0.021	0.021	0.015	0.015	0.015
			mean	2.684	1.873	1.862	2.221	1.410	1.399
			max	18.860	10.283	10.272	18.614	8.165	8.136
		M	min	0.092	0.092	0.092	0.058	0.058	0.058
			mean	5.383	4.573	4.561	4.898	4.088	4.077
			max	50.428	50.218	50.215	31.387	31.387	31.387
	1200	RC.gl	min	0.644	0.589	0.588	0.038	0.035	0.035
			mean	7.315	6.666	6.656	4.818	4.169	4.159
			max	32.261	32.261	32.261	30.471	30.471	30.471
		RC.sl	min	0.037	0.034	0.034	0.011	0.008	0.008
			mean	2.428	1.779	1.770	2.133	1.484	1.474
			max	13.964	10.583	10.549	13.910	8.962	8.938
		A.gl	min	0.031	0.028	0.028	0.011	0.008	0.008
			mean	2.469	1.820	1.811	2.175	1.526	1.517
			max	15.046	10.648	10.596	14.109	9.339	9.315
		A.sl	min	0.015	0.012	0.012	0.015	0.015	0.015
			mean	2.286	1.637	1.627	1.958	1.308	1.299
			max	13.952	10.258	10.250	13.608	7.985	7.960
		M	min	0.068	0.063	0.062	0.045	0.042	0.041
			mean	4.641	3.992	3.983	4.275	3.626	3.616
			max	40.891	40.168	40.157	30.926	30.926	30.926

Note: the table is divided in four sub-tables, each representing a specific combination of deductible (by column) and excess of loss (by row). Each sub-table presents minimum, average and maximum premium at the municipal level per each combination of structural typology (row) and number of storeys (column).

Figure 15: Optimal multi-hazard premium per square meter for one storey masonry buildings.



Note: the map represents a full coverage ($D = 0$, $E = 1500$ per square meter) policy, that has been estimated on N_c= 6217. The minimum value represented is 0.092 and therefore yellow municipalities should be interpreted as approximately 0. The maximum premium reported is 50.428.

Chapter 6

Conclusion and Future Developments

This thesis investigates the role of public-private partnerships in insurance for the management of natural disasters. Chapter 2 highlights the importance of co-operation between institutions and private individuals to achieve adequate risk reduction, which must pursue both mitigation and financing interventions. Although some countries have already joined successful public-private partnerships, some fragility in the systems have frequently shown up, largely linked to an insufficient understanding of the risks and to development plans that were not consistent with natural risk management objectives. Where data are lacking, a better dialogue with the whole community can allow for a greater understanding of the actual risk of the overall society. Much of the government's efforts must be directed towards listening to and actively involving the poorest and marginalized segments of the community, which constitute the most vulnerable layer of the population and have the greatest need for public support in the aftermath of an event. Involving and empowering all individuals also reduces risk by promoting more careful behavior. Likewise, it is important that governments ensure a coherent plan of action, aiming for responsible and controlled development.

In an increasingly interconnected and dangerous world, distinguishing risks and responsibilities is increasingly difficult and therefore public-private partnerships, especially in the insurance sector, are increasingly necessary. However, there are a number of critical issues in defining these partnerships, primarily dictated by the lack of information on natural hazards. Chapter 3 addresses this problem and presents an analysis of the risk of earthquakes and floods in Italy that allows to estimate expected losses in the absence of historical data. We found that seismic risk results in the highest expected losses at national level, but floods may generate the highest losses per square meter. The two perils differ in geographic extent: while the seismic risk is relevant for almost all the national territory, floods affect a limited area.

Chapter 4 deals with a further criticality of public-private insurance schemes: coordinating the different objectives pursued by the entities involved in the partnership. Insurers aim for profit and must guarantee compliance with certain solidity and solvency requirements, the governments need to guarantee protection for the entire population, and property owners show limited willingness to pay for insurance policies. A public-private insurance scheme must therefore both protect the solidity of the insurance industry and protect citizens, and should do so by avoiding overexposure of public assets. Chapter 4 proposes an insurance scheme with these characteristics and presents an application to Italian municipalities. The results show that, though expected losses generated by floods and earthquakes are considerably different, the amount of public funds needed to manage the two perils is almost the same.

As frequently happens, Italy is exposed to multiple natural risks that can have significant impacts and require important amounts of public funds. Chapter 5 extends the insurance model to the multi-hazard case and shows that in Italy the amount of public capital necessary for risk financing can be reduced by jointly managing earthquakes and floods. Along with this benefit from risk differentiation, multi-hazard policies allow the insurer to apply rates that are more geographically homogeneous, therefore favoring the perception of fair treatment among the population. Unfortunately, our results suggest that neither single- or multi-hazard policies in Italy are sustainable by the private market alone. Without the government, a private insurer would be forced to drive up premiums, which would not meet the demand and would therefore not be purchased. This result suggests the need for the government to intervene in the insurance market for natural disasters.

Since losses are quite high for the public sector too, our results suggest the need to introduce a mechanism for transferring the highest risk layers from the insurer to a third party. To this end, it might be interesting to explore the introduction of a public reinsurer and measure its impact on premiums and public funds needed. Alternatively, the public-private insurer can issue CatBonds. In particular, these would allow the public sector not to have to set up and manage a specific entity, and at the same time could sufficiently relieve insurance from the burden of extreme losses.

The estimates obtained here are based on the hypothesis that individuals are risk-averse with full access to information. Therefore, when looking for the maximum premium they are willing to pay, we have applied a utility function with risk aversion coefficient equal to 1. In practice, however, it is difficult to quantify the risk aversion of individuals who often show behaviors that are a little more risk neutral. The introduction of a risk aversion parameter in the utility function and its calibration on real data could offer new insights.

A further aspect that may deserve further studies is the role of the public sector on the market with respect to private insurers: here we have assumed that the government imposes the sale of a single product on the market, but free competition could change the balance between citizens and insurers. Citizens, or at least those living in lower risk areas, could in fact have more offers to choose from, and private insurance, which would be free to manage their customer portfolio as they prefer, could offer them a lower premium. It is therefore likely that private companies will take over the less risky areas, leaving the public insurer with an extremely risky portfolio and thus exposing the government to a greater probability of losing public funds.

At last, in this work we have decided to analyze the two natural phenomena that most afflict the Italian territory. However, Italy is also affected by other risks, among which landslides and volcanic eruptions, which could be introduced into the multi-hazard policy. Extending our insurance model by introducing the correlation between the typologies of risks covered would allow for the construction of more comprehensive policies. There are also other aspects of the risks studied here that deserve further study, including the effect of climate change on flood estimates and the consequent adjustment of premiums.

The research projects carried out in this thesis have led to two further works that still constitute my research today. Together with my advisor Fabio Pammolli and Giovanni Bonaccorsi, we are furthering investigating the vulnerability of the Italian municipalities. Our work aims at the definition of an index representing the financial vulnerability to natural risks. The index will contain and relate information about natural riskiness, demographic framework, and financial status of the municipalities.

During my visiting period in Wellington, New Zealand, I initiated a further research project with my visiting supervisor, prof. Ilan Noy, and Francesca Marta Lilja Di Lascio. We are working on the definition of a risk-based premium for earthquake insurance in New Zealand that captures the effect of spatial correlation among insured assets. As already discussed in this thesis, natural disasters are characterized by spatial micro-correlations which are difficult to capture but might increase the likelihood of extreme events. The non-homogeneous distribution of population over the national territory coupled with high seismic exposure makes the effect of spatial correlation extremely relevant in the Country. In fact, New Zealanders tend to gather in big cities, while extensive areas are left completely uninhabited. Therefore, an earthquake hitting a densely inhabited city will trigger several claims, while a similar or stronger earthquake far enough from those cities may not damage any asset. Including micro-spatial correlation in rating allows for the identification of critical areas that may challenge the insurance business and ensures that insurers build the reserves needed to cope with tail events. In order to properly represent annual losses, we are implementing a multilevel regression model.

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