RIGA TECHNICAL UNIVERSITY

Andrea Jonathan Pagano

THE MITIGATION OF SOCIO-NATURAL HAZARDS THROUGH SMART INSURANCE CONTRACTS

Summary of the Doctoral Thesis

RTU Press
Riga 2024

RIGA TECHNICAL UNIVERSITY
Faculty of Natural Sciences and Technology
Institute of Energy Systems and Environment

Andrea Jonathan Pagano
Doctoral Student of the Study Programme "Environmental Engineering"

THE MITIGATION OF SOCIO-NATURAL HAZARDS THROUGH SMART INSURANCE CONTRACTS

Summary of the Doctoral Thesis

Scientific supervisors
Professor Dr. sc. ing.
FRANCESCO ROMAGNOLI

Assoc. Professor Dr. sc. econ.
EMANUELE VANNUCCI

Assist. Professor Dr. sc. ing.
MAKSIMS FEOFILOVS

RTU Press
Riga 2024

Pagano, A. J. The Mitigation of Socio-natural Hazards through Smart Insurance Contracts. Riga: RTU Press, 2024. 49 p.

Published in accordance with the decision of the Promotion Council “RTU P-9” of 26 June 2023, Minutes No. 173.

Cover image developed using ChatGPT.

https://doi.org/10.7250/9789934370373
ISBN 978-9934-37-037-3 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on 27 March 2024 at 14.00 at the Faculty of Natural Sciences and Technology of Riga Technical University, Āzenes iela 12/1, Room 115.

OFFICIAL REVIEWERS

Professor Dr. sc. Sara Landini
University of Florence, Italy

Professor Dr. sc. Fausto Marincioni
Polytechnic University of Marche, Italy

Professor Dr. sc. ing. Gatis Bažbauers
Riga Technical University

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Andrea Jonathan Pagano (signature)

Date: 23.02.2024

The Doctoral Thesis has been written in English. It consists of Introduction, 3 chapters, Conclusions, 23 figures, 21 tables, and 10 appendices; the total number of pages is 112, not including appendices. The Bibliography contains 217 titles.

TABLE OF CONTENTS

Introduction

Climate change has amplified the frequency and severity of natural calamities, encompassing a growing trend of extreme climatic events and facing substantial threats to global communities, ecosystems, and economies. Within this background, the intertwining of urbanization and climate change, impacting societal and economic dimensions, pose key challenges for European urban centres in the foreseeable future.

If not properly addressed, these socio-natural hazards can escalate into catastrophic events, exposing communities to severe physical and financial losses. Over the past 15 years, there has been a 2 % increase in disasters, leading to economically relevant losses [2] and prompting scientific and professional communities to seek novel insurance methods for resilient risk reduction.

In its 2021 report [1], Swiss Re assessed more than 50 severe flood events globally, resulting in nearly 26,000 lives lost at the EU level. Overall, the world incurred economic losses totaling $80 billion, with approximately 50 % covered by insurance payments [3].

In 2021, global insured damages from natural catastrophes reached €100 billion, making it the fourth most expensive year since 1970 [4]. This upward trend, ongoing for 40 years, is expected to intensify with climate change as global warming contributes to environmental-related disasters.

A spectrum of financial instruments has emerged to finance projects reducing hazardous impacts on communities, standing out as a powerful and versatile tool for managing the financial consequences of natural disasters. For instance, catastrophe bonds can be employed to transfer risks tied to potential disasters to financial markets, while resilience bonds have been introduced to support resilient infrastructure initiatives, reducing the susceptibility to large-scale risks in potential disasters.

Insurance companies, acknowledging climate change effects, adjust benchmark figures, anticipating increased loss potentials and shorter high-intensity recurrence periods [5]. Prevention and adaptation strategies aim to limit negative consequences, emphasizing the need for a proactive approach from the insurance sector.

The Sendai Framework for Disaster Risk Reduction [6] recognizes insurance's crucial role in resilience, supporting recovery efforts and incentivizing risk reduction measures. A collaborative approach involving governments, the private sector, and communities is essential to develop comprehensive risk reduction strategies.

Disaster risk reduction policies are vital for social welfare, economic growth, and environmental well-being. Insurance plays a crucial role in mitigating financial impacts, aligning with disaster risk reduction (DRR) strategies in the Sendai Framework.

An integrated approach involving the insurance industry, governments, donors, NGOs, and academia has evolved, exploring the dynamic nexus between socio-natural hazards, insurance, and technological innovation [7]. Smart insurance contracts, leveraging innovative technical solutions like blockchain technology, represent a paradigm shift in risk management, offering real-time data analysis and adaptive coverage options. These contracts improve the robustness of calculating potential losses, streamline insurance processes, and contribute to resilient practices and infrastructure [8].

Given this background, it is evident that disaster risk reduction policies play a pivotal role in promoting social welfare, fostering economic growth, and safeguarding environmental well-being. Within these strategies, insurance becomes a crucial and flexible instrument for effectively mitigating a profound financial impact of socio-natural disasters. Their role in supporting community and urban resilience increased. In this perspective insurance mechanisms are becoming essential drivers for managing the risks associated with climate change.

This Thesis aims to analyse and explore the role of insurance in addressing socio-natural hazards by introducing a proactive approach towards the investments and support of disaster risk reduction strategies, which not only transfer risk but actively reduce it. Moreover, it delves into the domain of behavioural economics, exploring the capacity of smart insurance contracts to incentivize behavioural changes that foster disaster preparedness, promote risk mitigation, and enhance societal adaptation.

This Doctoral Thesis delves into insurance's multifaceted and multidisciplinary role in protecting individuals, communities, and societies against the financial burdens of socio-natural disasters. The research seeks to provide a comprehensive understanding of the dynamic's mechanisms through which insurance functions as a risk transfer and risk reduction instrument. It also examines its potential for influencing disaster preparedness, resilience, and urban-societal adaptation. By combining empirical evidence, theoretical insights, and case studies, this research investigates the evolving role of disaster insurance, including the challenges and opportunities it presents in the face of an increasingly unpredictable climate with the goal to support urban policy planning by investigating the role of insurance mechanisms in protecting against climate change-related risks.

Objective and Tasks of the Doctoral Thesis

The Thesis aims to develop a quantitative assessment model that can support insurance companies and urban planners in building urban resilience against socio-natural hazards at a local level by implementing innovative insurance mechanisms. The main objectives for achieving the goal are:

- Examination of quantitative methodologies commonly utilized by insurance companies to evaluate risk premiums.
- Identification of the state-of-art of key concepts, models, and frameworks employed in evaluating risk within insurance policies and investigation of any recent developments, innovations, or emerging trends in the quantitative assessment of risk premiums within the insurance sector.
- Evaluation of the potential gaps in technological advancements, data analytics, and risk premium evaluation.
- Developing a novel conceptual framework for a novel risk insurance mechanism, evaluating the insurance system as pivotal role towards disaster risk reduction and mitigation with insights on the use of smart contracting as an adaptive and resilient insurance scheme with an emphasis on floods.
- Including selected case studies that exemplify the application of the developed framework in determining risk premiums referring to socio-natural hazards.
- Integration of the main findings from the case studies into a model developed and applied in an urban Latvian context for assets and communities prone to flood by developing a system dynamics model.
- Providing suggestions for further research on the topic and implementation of the developed tool.

Hypothesis of the Thesis

Considering the overall concern towards climate change and the need to mitigate the risks of socio-natural hazards, new and more proactive insurance tools may play a key role. However, there is limited research on using and implementing resilience financial tools within the insurance sector. This constraint raises concerns because it could result in growing long-term damage costs as the threat of climate-related calamities increases. Thus, this research focuses on an integrated and multidisciplinary research to evaluate the dynamics within an insurance sector's proactive role.

To fill in this knowledge gap and assess the usefulness and efficiency of new insurance instruments embedded in a proactive role of the insurance sector as a driver for risk mitigation and prevention measures, the core question of the proposed case study is: *to what extend the applications of a novel insurance mechanism can be used for co-financing disaster resilience projects for mitigation and adaptation strategies enhancing community resilience against weather-related hazards*

The hypothesis of this Doctoral Thesis is that the integration of smart insurance contracts, driven by advanced technologies, data analytics, and real-time risk assessment, can significantly enhance the resilience of communities and reduce the socio-economic impact of natural disasters and socio-natural hazards, leading to more sustainable and adaptive disaster risk management strategies. This hypothesis postulates that the dynamic and proactive nature of smart insurance contracts, when effectively implemented, improves financial risk transfer, drives behavioural change, promotes disaster preparedness, and enhances societal adaptation to mitigate such hazards' social and environmental consequences. The hypothesis to be examined relies on the postulate that a multidisciplinary approach, encompassing engineering perspective, legislative implementation, and insurance dynamics, can be beneficial in covering the limitations of traditional insurance methods in disaster risk reduction and natural hazard mitigation.

Scientific Significance of the Doctoral Thesis

As socio-natural hazards continuously threaten the resilience of communities and ecosystems globally, there is an urgent requirement for new perspectives, innovative solutions, and practical approaches to disaster risk reduction. This doctoral research stands as an interface and intersection of cutting-edge technologies, behavioural science, and environmental adaptation, providing a unique viewpoint on how smart insurance contracts can drive transformation in disaster risk management.

Through a multidisciplinary lens centred on the key role played by insurance in DRR mechanisms, this research represents an improvement towards comprehending the opportunities and challenges that lie ahead in making our societies more resilient, adaptive, and sustainable in the face of socio-natural hazards.

The scientific topicality of this research is underlined by the current state-of-art of the insurance sector related to climate-change-linked disasters threatening sustainable development worldwide. In fact, it is expected that adverse climate change effects will significantly increase the frequency, intensity, spatial extent and duration of socio-natural hazards. Moreover, the insurance market has not yet found a valid approach to face the effects of climate change in combination with the increasing threats of natural hazards. This poses a high risk for disaster events, with a particular focus on mitigative tools.

This doctoral study's unique approach to tackling the complex and interconnected problems presented by socio-natural hazards is what makes it innovative from a scientific standpoint. This research contributes to the improvement of research in several innovative ways:

1. Application of smart contracting and IT solutions in the insurance sector to make disaster management more resilient, efficient, and effective.
2. Key role of a proactive risk management within insurance frameworks providing financial indemnity after a disaster by implementing smart insurance contracts to actively reduce risks and vulnerabilities and the recovery time of a damaged asset.
3. Investigating how smart insurance contracts can improve urban planning if exposed to risk, with an emphasis on flood, supporting disaster preparedness, and promoting risk-reduction actions.

The scientific novelty of the Thesis research thus lies in its pioneering exploration of smart insurance contracts as a novel approach to addressing the complex challenges of socio-natural hazards. By evaluating the impact of integrating advanced technologies, behavioural incentives, within a proactive risk management closely involving the insurance companies, and comprehensive urban adaptation strategies, this research opens new ways for more effective, sustainable, and adaptive disaster risk mitigation.

Practical Significance of the Doctoral Thesis

The findings of the Doctoral Thesis are significant for urban planners and risk reduction managers, providing knowledge and evidence of how a proactive role of insurance can contribute to strengthening urban resilience aligned with the Sendai Action Plan 2015–2030 for DRR against socio-natural hazards. Moreover, it represents a potential new paradigm for the insurance industry.

The approaches and methods developed in the Thesis have been defined on the gaps that urban contexts face when developing and implementing DRR action plans, which are addressed in the proposed research method.

As communities worldwide tackle increasing vulnerability to floods, the study examines the benefits and applications of employing innovative insurance solutions. By integrating advanced technologies and risk mitigation strategies, the research offers practical insights into how smart insurance contracts can play a pivotal role in enhancing resilience, reducing losses, and fostering sustainable and more resilient approaches to flood management.

The study's findings contribute to a better understanding of the effectiveness of leveraging smart insurance mechanisms for mitigating the impact of floods on communities and their socio-economic environments. The Thesis describes the role of smart insurance contracts in supporting a dynamic and proactive insurance, creating a better decision strategy for coping against socio-natural hazards, with an emphasis on floods.

The developed tool implemented in a system dynamics model fills the existing and actual knowledge gaps identified in scientific literature by providing a novel approach for investigating disaster risk reduction mechanisms and insurance dynamics against socio-natural hazards.

Insurance companies can use the developed model with national and local urban contexts for resilience strategies against natural hazards and to develop tailored business models.

The contractual and recursive tool structure includes social, economic, environmental, and infrastructural aspects of the insurance system and disaster risk reduction urban resilience assessment. Thus, applying the developed tool also supports the link between the disaster risk reduction field and the policy planning of other sectors like urban planning, improving public investment in risk reduction measures, and providing relief for the immovable assets sector.

This research incorporates case studies and practical applications of smart insurance contracts, offering empirical evidence and practical insights that can inform policy and industry decisions. It bridges the gap between theory and practice, making the findings immediately relevant to stakeholders.

The recommendations and frameworks developed in the study can also be eventually integrated into existing urban planning at the EU, national, and regional levels. The proposed model provides a useful decision support tool for disaster management, moving toward a different proactive role for insurance companies towards a more resilient, sustainable and safe future.

Research Framework

The Thesis proposes a final system dynamics model based on a novel Bayesian adaptive insurance scheme. This mechanism incorporates smart contracts and is further applied in developing a specific dynamic urban assessment for socio-natural hazards, with a specific focus on floods in the Latvian context.

This model is designed to assess the potential of insurance playing a proactive role in disaster risk reduction within socio-natural hazards (see Fig. 1), comparing it to conventional insurance mechanisms. Various methods for calculating insurance premiums for assets exposed to socio-natural hazards are examined to achieve this goal. These methods are further integrated into developing a new conceptual framework, shaping a novel definition and implementation of risk insurance. This process is elucidated in Fig. 1, in research Steps 1 to 3.

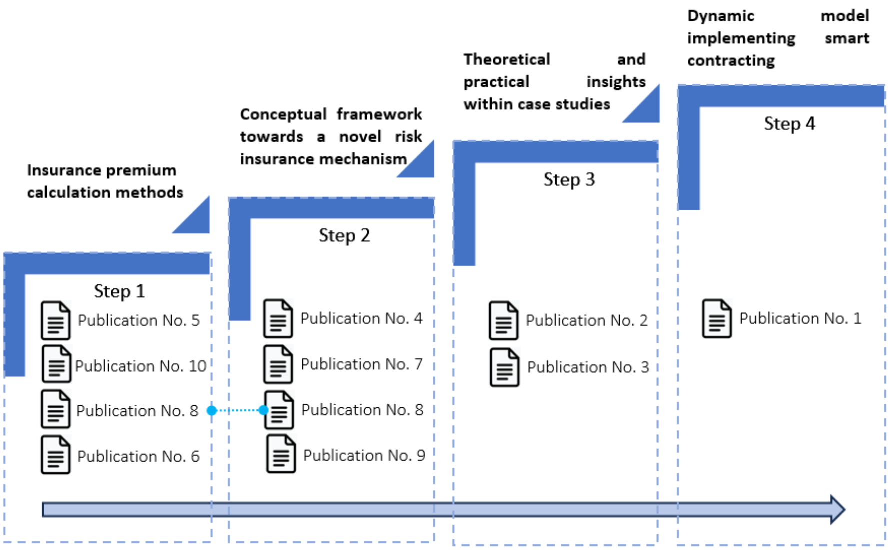

Fig. 1. The research framework of the Doctoral Thesis.

The Thesis uses the system dynamics modelling approach to assess the potential advantages of a novel insurance mechanism based on smart contracting for urban assets and communities exposed to socio-natural risks. This approach addresses the underlying risks of disasters, in contrast to a traditional disaster insurance strategy that primarily focuses on providing financial security for asset recovery. The Thesis, developed and validated through ten scientific publications, explores various aspects of engineering, legal considerations, and quantitative theoretical and practical systems. It introduces an innovative tool for implementing socio-natural risk mitigation strategies, emphasizing the proactive role that insurance can play.

The overview of the Thesis is presented in Fig. 1, outlining four steps and their corresponding predefined objectives. Figure 1 illustrates the four primary interrelated studies and their detailed results, which are presented in the respective sections of the Thesis.

Approbation

The results of the author's research have been presented and discussed in a number of scientific conferences and published in 10 peer-reviewed scientific journals.

1. M. Feofilovs, **A. J. Pagano**, E. Vannucci, M. Spiotta, and F. Romagnoli. Climate change-related disaster risk mitigation through innovative insurance mechanism: a System Dynamics model application for a case study in Latvia International. *Risks*, 2024, vol. 12, no. 43, pp. 1–23.
2. **A. J. Pagano**, F. Romagnoli, and E. Vannucci. Non-incomes risk mitigation mechanisms for cultural heritage: role of insurances facing Covid-179. *Environ. Clim. Technol.*, 2022, vol. 26, no. 1, pp. 871–882.
3. **A. J. Pagano**, F. Romagnoli, and E. Vannucci. COVID-19 Effects on Cultural Heritage: The Case of Villa Adriana and Villa D'Este. *Environ. Clim. Technol.*, 2021, vol. 25, no. 1, pp. 1241–1252.
4. **A. J. Pagano**, F. Romagnoli, and E. Vannucci. Climate change management: a resilience strategy for flood risk using Blockchain tools. *Decis. Econ. Financ.*, 2021, vol. 44, pp. 177–190.
5. **A. J. Pagano**, F. Romagnoli, and E. Vannucci. Quantitative and Financial Aspects of Resilience Bonds in the Context of Recursive Insurance Contracts. A Cost Benefit Analysis. *Environ. Clim. Technol.*, 2020, vol. 24, no. 3, pp. 387–402.
6. **A. J. Pagano**, F. Romagnoli, and E. Vannucci. Insurance against Natural Hazards: Critical Elements on the Risk Premium Evaluation in the Italian Context. *Environ. Clim. Technol.*, 2020, vol. 24, no. 3, pp. 373–386.
7. **A. J. Pagano**, E. Vannucci, and F. Romagnoli. Flood risk: financing for resilience using insurance adaptive schemes. *International Journal of Plant Chemistry, Soil Science and Plant Nutrition of the University of Pisa, The Effects of Climate Change Agrochimica – Special Issue*, 2019, pp. 305–322.
8. A. Bellieri dei Belliera, M. Galeotti, **A. J. Pagano**, G. Rabitti, F. Romagnoli, and E. Vannucci. Flood risk insurance: the Blockchain approach to a Bayesian adaptive design of the contract. In *Afir ERM*, 2019, pp. 1–19.
9. **A. J. Pagano**, F. Romagnoli, M. Feofilovs, and E. Vannucci. Implementation of Blockchain Technology in Insurance Contracts against Natural Hazards: A Methodological Multi-Disciplinary Approach. *Environ. Clim. Technol.*, 2019, vol. 23, no. 3, pp. 211–229.
10. **A. J. Pagano**, M. Feofilovs, and F. Romagnoli. The relationship between insurance companies and natural disaster risk reduction: overview of the key characteristics and mechanisms dealing with climate change. *Energy Procedia*, 2018, vol. 147, pp. 566–572.

Other scientific publications

1. M. Feofilovs, A. Gravelsins, **A. J. Pagano**, and F. Romagnoli. Increasing resilience of the natural gas system with implementation of renewable methane in the context of Latvia: A system dynamics model. *Energy Procedia*, 2019, vol. 158, pp. 3944–3950.

Reports at scientific conferences

1. A. J. Pagano, F. Romagnoli, and E. Vannucci. Non-incomes risk mitigation mechanisms for cultural heritage: role of insurances facing Covid-19. International scientific conference of Environmental and Climate Technologies, CONECT 2021. Riga, Latvia, May 11–13, 2022.
2. A. J. Pagano, F. Romagnoli, and E. Vannucci. COVID-19 Effects on Cultural Heritage: The Case of Villa Adriana and Villa D'Este. International scientific conference of Environmental and Climate Technologies, CONECT 2021. Riga, Latvia, May 11–13, 2021
3. A. J. Pagano, F. Romagnoli, and E. Vannucci. Quantitative and Financial Aspects of Resilience Bonds in the Context of Recursive Insurance Contracts. A Cost Benefit Analysis. International scientific conference of Environmental and Climate Technologies, CONECT 2020. Riga, Latvia, May 13–15, 2020.
4. A. J. Pagano, E. Vannucci, and F. Romagnoli. Flood risk: financing for resilience using insurance adaptive schemes. Giornata di studio, Le attività dell'Università di Pisa sul tema degli effetti del cambiamento climatico. Pisa, Italy, December 6, 2019.
5. A. Bellieri dei Belliera, M. Galeotti, A. J. Pagano, G. Rabitti, F. Romagnoli, and E. Vannucci. Flood risk insurance: the Blockchain approach to a Bayesian adaptive design of the contract. AFIR-ERM Colloquium 2019, Innovating Actuarial Research on Financial Risk and ERM. Florence, Italy, May 21–24, 2019.
6. A. J. Pagano, F. Romagnoli, and E. Vannucci. Implementation of Blockchain Technology in Insurance Contracts against Natural Hazards: A Methodological Multi-Disciplinary Approach. International scientific conference of Environmental and Climate Technologies, CONECT 2019. Riga, Latvia, May 15–17, 2019.
7. A. J. Pagano, M. Feofilovs, A. Gravelsins, and F. Romagnoli. Increasing Resilience of the Natural Gas System with Implementation of Renewable Methane in the Context of Latvia: A System Dynamics Model. 10th International Conference on Applied Energy "ICAE2018". Hong Kong, China, August 22–25, 2018.
8. A. J. Pagano and O. Tumule. Comparative bankruptcy procedural law aspects of cross-border and domestic avoidance action. XIX International Scientific Conference: Latvia 100: Expectations, Achievements and Challenges. Riga, Latvia, April 19, 2018.
9. A. J. Pagano, M. Feofilovs, and F. Romagnoli. The relationship between insurance companies and natural disaster risk reduction: overview of the key characteristics and mechanisms dealing with climate change. International scientific conference of Environmental and Climate Technologies, CONECT 2018. Riga, Latvia, May 16–18, 2018.
10. M. Feofilovs, A. J. Pagano, and F. Romagnoli. Market development and support schemes for biomethane: SWOT analysis in context of Latvia. International scientific conference of Environmental and Climate Technologies, CONECT 2018. Riga, Latvia, May 16–18, 2018.

1. METHODOLOGY

Aligning with the key research questions specified in the research hypothesis and the research objectives, and emphasizing its scientific significance, this doctoral study endeavours to articulate the conclusive proposal for a system dynamics model based on a novel Bayesian adaptive insurance scheme. This mechanism incorporates smart contracts being considered as a dynamic urban assessment tool for socio-natural hazards, with a specific focus on floods in the Latvian context.

This model is designed to assess the potential of insurance playing a proactive role in disaster risk reduction within socio-natural hazards (see Fig. 1.1), comparing it to conventional insurance mechanisms. Various methods for calculating insurance premiums for assets exposed to socio-natural hazards are examined to achieve this goal. These methods are further integrated into developing a new conceptual framework, shaping a novel definition and implementation of risk insurance. This process is elucidated in Fig. 1.1, in research Steps 1 to 3.

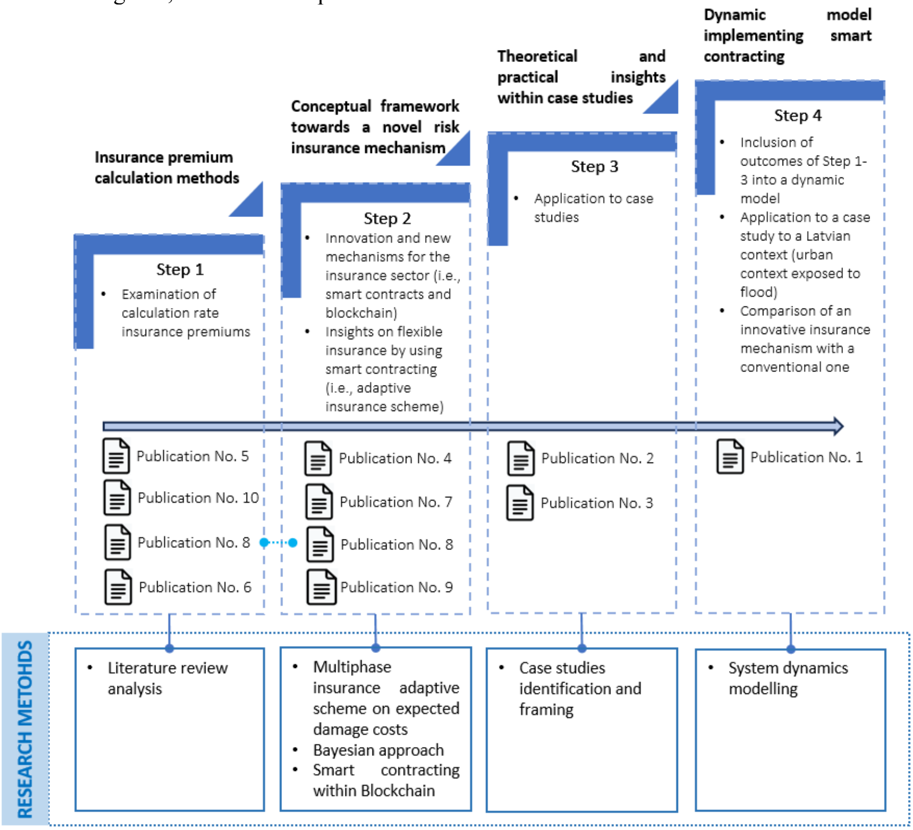

Fig. 1.1. Research framework and methods of the Doctoral Thesis.

The final research step aims to consolidate the specific outputs derived from research Steps 1 to 3. These findings will be incorporated into assessing the proactive role that insurance companies can play in investing in risk reduction projects. The model will be tested using the case study focused on an urban context in Latvia exposed to floods.

Based on ten peer-reviewed research articles (Publications 1–10) presented at international scientific conferences and published in international scientific journals, the research framework has been used to address the specific research objectives and questions. These articles detail individual case studies employing different methodologies integrated into a dynamic urban resilience assessment tool for natural hazards.

The Thesis comprises an introduction and four chapters: a literature review, research methodology, results and discussion, and final conclusions. The introduction outlines the aim of the Doctoral Thesis, the scientific and practical significance of the developed tool, and the scientific articles published on the Thesis topic. The approbated results are based on the list of publications presented at international scientific conferences (see the Approbation section).

Chapter 1 presents a literature review analysing how the insurance sector deals with socio-natural hazards. This section explores the current relevance of the research field, specific terminology, with a focus on trends in increasing the frequency of disasters linked to climate change. It defines types of socio-natural hazards, examines insurance's role in changing exposures to socio-natural disasters, and discusses the roles of smart contracting and blockchain technology as resilience-enhancing strategies within the insurance sector. Traditional disaster risk reduction assessment within the insurance sector is also covered.

Chapter 2 of the Thesis details each step of the research methodology, leading to the scientific articles that validate the research objectives. Chapter 3 of the Doctoral thesis focuses on the results achieved, particularly emphasizing the development and application of the dynamic evaluation of an innovative insurance mechanism in response to a specific urban resilience assessment tool for natural hazards.

The final chapter provides overall conclusions and recommendations for applying the tool in policy planning.

1.1. Insurance premium calculation method

This stage involves an extensive literature review to identify existing premium calculation models, analysing historical data and case studies to understand current insurance industry practices using statistical and actuarial methods to assess risk factors and their impact on premium calculations. The objective is to explore and evaluate various methodologies for calculating insurance premiums, with a focus on assets exposed to socio-natural hazards (see Publications 5, 8, and 10).

Insurance calculation method portfolio

Given the specific nature of insurance derivation, the first methodological step is inherent in calculating the premium rate (see Publications 5, 6, 8, and 10). The author attempts to highlight standard steps for explaining the mechanisms related to the general rate within the insurance framework.

A summary of the main indicators of the insurance portfolio is reported in Table 1.1.

Table 1.1

The Main Indicators of the Insurance Portfolio [9]

Main indicators	Characteristic
Diversification of portfolio insurance	The high level of portfolio diversification and lack of dependence on large customers ultimately have a positive effect on the final financial result of insurance operations.
The stability of the insurance portfolio	The level of stability of the insurance portfolio is affected, first of all, by a high level of extension of contracts of insurance. Stable insurance portfolio has a positive effect on the profitability of insurance operations.
Unprofitability by activity	Group loss ratio reflects the correctness of payment, which is covered by insurance.
The technical result corresponds to the lines of business	Characterizes the ratio of earned premium to the cost of the lines of business; it is necessary to determine the profitability of the business.
The relative magnitude of the risks taken	The relative magnitude of the risks taken by ratio to the size of equity determines the susceptibility of catastrophic risks.

Forecasting the portfolio and evaluating the profitability of current and future insurance operations is possible through a thorough examination of the insurance portfolio covered by contracts (type of insurance as a whole or by-products). The assessment of the insurance portfolio's quality is a key factor in the company's final grade. A complete examination of the current insurance portfolio is necessary to set goals for the medium- and long-term periods by business lines (products and/or insurance) and to ensure the financial security and solvency of the insurance firm [10].

Investigation of the portfolio's subjective qualities reveals problematic facets. These qualities are arbitrary because the number of client companies influences the client-to-company ratio and the company's reputation. Additionally, the quantity and seriousness of regulatory authorities' complaints (compared to the volume of contracts) suggest the number of unhappy clients and, ultimately, the extent to which the customer fully covers each client's insurance products.

More details are described in Section 2.1 of the Doctoral Thesis.

Static methods in an insurance company. Portfolio analysis

Calculating an underwriting loss is the calculating approach that provides the most information. Unprofitability in insurance operations is a measure of how well an insurer is performing its activities other than life insurance. This measure can be calculated for all types of insurance or for each type individually. The sequence of calculation is determined by the basis of the calculation, which may be underwriting, the operational year, or the time at which a loss first occurs (the insured event).

The proportion of insurance payments to accumulated (paid or earned) premiums at the end of the underwriting year includes reserves for incurred but unreported claims as well as the estimated allowance for losses.

At the end of the calendar year, the ratio is determined by subtracting the reserves for insurance payments (losses) from the denominator, which includes premiums paid during the calendar year, from the numerator, which includes reserves for insurance payments (losses) at the end of the calendar year. For calculating on-year loss events, as showed in Eq. (1) the denominator is the premium received during the calendar year, with the numerator being insurance payouts for insured events that happened during the calendar year, plus insurance reserves for losses sustained during the calendar year [11].

$$Loss\ Ratio = \frac{Loss\ Adjustments}{Premium\ Earned}\ Expense\ Ratio = \frac{Underwriting\ Expenses}{Net\ Premium\ Written} \tag{1}$$

$$Combined\ Ratio = (Loss\ Ratio + Expense\ Ratio)$$

The loss ratio, often calculated as paid losses to premiums received in the underwriting year, provides a quick result but may not account for segment losses, hindering a comprehensive tariff policy review [12].

Some companies use cash settlement loss for rapid portfolio assessment, correlating paid losses over a period with premiums received in the same period. However, this method lacks consideration for segment losses and prevents a thorough tariff policy review.

Calculating the average insurance premium and conducting an analysis on commission payments are essential for tariff revision and formulating a cost-effective portfolio. Statistical data on accumulated losses and average damage size aid in determining the highest probability of insured events. Catastrophe scenarios, especially related to natural hazards, are evaluated through average annual loss (AAL) and exceedance probability (EP) curves. These curves assist insurers in understanding potential losses' size and distribution.

The EP curve helps determine the probable maximum loss (PML) for a portfolio in a specific timeframe due to natural hazard occurrences. It allows insurers to assess the total loss amount for a specific probability level, aiding in risk management decisions.

To enhance the discussion, the authors should present theoretical questions in a table and graph format. This visual representation clarifies how insurance companies determine risk and pricing based on a numerical base, particularly regarding the percentage of exceedance probability [13].

More details are described in Section 2.1 of the Doctoral Thesis.

1.2. Conceptual framework towards a novel risk insurance mechanism

The second methodological step aims to frame and evaluate a conceptual framework towards a novel risk insurance mechanism, including the insights gained from the premium calculation methods (see Publications 4, 7, 8, and 9).

This research method is a step to synthesize findings from the premium calculation exploration, identifying gaps and shortcomings in existing insurance mechanisms with the aim to further propose innovative concepts and structures for risk insurance, considering both theoretical basis and practical implications.

Moving towards a new paradigm involving insurance mechanism in disaster risk reduction strategy emphasizes resilience's interdisciplinary nature, which includes the social, economic, institutional, infrastructure/engineering, and community structures and any related data.

Multiphase contracts and blockchain. Italian context

The multi-period implementation in smart insurance contracts relies on periodic changes in contractual structure, facilitated by blockchain technology and information from certified external sources. Key aspects of this multi-phase contract include bilateral provisions, aleatory nature, information technology utilization, blockchain integration, real-time data flow, and automatic renegotiation.

Bilateral provisions involve the insured paying predetermined intervals of insurance premiums, with compensation provided by the company upon the occurrence of the insured event. Despite adopting the standard insurance contract scheme, it can be burdensome [14]. The aleatory nature indicates that the occurrence of the insured event remains unknown, even after identification and documentation, emphasizing information technology [15].

Information technology plays a significant role, with contract terms agreed upon through an online platform using blockchain technology. Digital signatures, a part of this process, contribute to consent mechanisms [16]. Blockchain technology, a structured consisting of nodes and arcs, is adaptable to the conventional supply chain model, capturing organizational and network risks.

Real-time data flow enables the blockchain contract structure to receive and incorporate data about the insured asset and its environment, allowing regular changes to the contract's initial terms [13]. Automatic renegotiation, or automatic consensus, empowers the contract to adjust its terms regularly based on incoming data [17].

The methodological phase involved a study of Italian insurance legislation through collaboration with local insurance companies. Describing the typical insurance contract within the Italian Civil Code, as outlined in Article 1882, emphasizes the insurer's agreement to compensate for losses or provide a lump sum or annuity in case of specific incidents [18]. The characteristic of being burdensome is fundamental to this definition.

Regarding *alea*, risk is tied to the hypothetical chance of a destructive occurrence affecting the subject's interest, remaining in a latent state until the hypothetical possibility is realized. The risk must be objectively uncertain, caused by external factors, and harmful to the protected interest. Its existence in a latent state before realization adds complexity to its nature [19].

The absence of a state *ab origine* determines the *ex tunc* validity of the contract due to a lack of cause (Article 1895). The termination of the contract leads to the termination of the relationship, highlighting the state of objective and absolute uncertainty essential to its features. The probabilistic forecast of a detrimental fact, human or natural, must exist at the time of policy adherence. Including this feature in the new contract is not prevented.

IT aspects related to blockchain and real-time data flow involve verifying data flow, certifying received data, and ensuring payment when delays occur [20]. Elements like compensation and *alea* are inherent *ex se*, while others, such as blockchain, are post-implementation. A smart contract, conceived as a multiphase contract, aligns with the resilient method's mitigation process [21].

The process involves initial data collection on climatic phenomena and their effects on flood events, where blockchain certifies data reliability. It includes contract stipulation for insurance and financing of mitigation work, certifying the construction timetable, and completing the mitigation work [22].

The synergy of big data's new opportunities for collection, covering health, driving, climate, and seismic risks, along with blockchain's role in validation, creates ideal conditions for the widespread adoption of smart contracts in the insurance industry.

More details are described in Section 2.2 of Doctoral Thesis.

Quantitative and Bayesian approaches

Th research has focused, moreover, on one of the currently popular areas of focus for employing a Bayesian adaptive approach in a multi-period insurance plan, specifically examining the risk linked with severe weather occurrences, with a particular emphasis on investigating flood risk.

It is necessary to use a multidisciplinary approach to conduct this type of research because the macro-fields involved include actuarial science for the quantitative analysis, engineering expertise for assessing flood risk in a particular area, legal perspective to provide proper legal support for smart contracts in a multiperiodic scenario, and informatics expertise to describe the process made possible by blockchain technology [23].

In order to maximize the total territorial resilience, it is necessary to evaluate how prospective infrastructure enhancements, including physical and/or soft measures, can be made.

In this context, it is necessary to create quantitative or semi-quantitative methodologies that could assess the optimization of the capacities defining the resilience of an urban system and/or community in a manner akin to a cost-benefit analysis.

In this regard, during the past ten years, special focus has been placed on the selection of specialized risk assessment techniques with a focus on the measurement of vulnerable regions and community at risk [24].

The engineering perspective, which is emphasized by the technical aspect of this method, emphasizes the significance of considering the critical infrastructure's vulnerability assessment, particularly as it relates to urban networks at risk for natural disasters like floods [25].

As the methodology can identify resilience characteristics at the urban scale and to plan for enhancing strategies, the study of Serre et al. [26] proposes an assessment on the impacts of potential disruption of urban networks on the evaluation of the capacities that characterized the level of resilience of an urban environment.

More details are described in Section 2.2 of the Doctoral Thesis.

1.3. Theoretical and practical insights in case studies

The third methodological step in this research aims to gain theoretical and practical insights into applying a novel risk insurance mechanism through case studies. This involves selecting and applying the developed conceptual framework to assess the effectiveness of the mechanism in real-world scenarios, incorporating qualitative and quantitative data, interviews, and on-site observations.

Two case studies, Villa Adriana and Villa d'Este, representing cultural heritage prone to social-natural hazards, were chosen. Before the in-depth analysis, two key implementation phases were considered. The first phase involved cross-searching the national Italian and UNESCO databases for cultural sites of economic and social value. This research, conducted on the UNESCO online page, aimed to understand the impact of the pandemic on Italian cultural heritage, supporting financial analytical analysis by comparing data with the UNESCO list.

The second methodological aspect focused on legal/regulatory dissemination, examining provisions influencing cultural heritage at the national level. This involved an analytical examination of laws up to the application of binding legislation.

The subsequent methodological step quantitatively analysed potential catastrophic events and associated economic effects, focusing on balance sheets from relevant websites for the last three years. This allowed for a scalar projection of key indicators between costs and incomes, providing a progressive historical analysis.

The final part explored the consequences of the pandemic for cultural activities, especially national sites, through research for statistical data and reports. This comprehensive approach integrates diverse methodologies for a thorough understanding of the novel risk insurance mechanism's applicability in safeguarding cultural heritage.

More details are described in Section 2.3 of the Doctoral Thesis.

1.4. Smart contracting implemented in dynamics model

The latest methodological approach endeavours to construct a system dynamics model incorporating smart contracting to simulate and evaluate the proposed innovative risk insurance mechanism. Utilizing system dynamics modelling techniques to represent the dynamic interactions among various components of the insurance system appears to be the most suitable tool for framing the complex interactions. Implementing smart contracting features within the model automates processes and simulates real-time responses, as detailed in Publication 1.

This approach also holds relevance in the context of urban disasters, where disaster management remains a challenging issue necessitating creative solutions for the development of urban resilience measures. This perspective gains added significance when considered within the framework of sustainable energy and climate action plans (SECAPs) for Municipalities [27].

For example, in the scholarly work of Serre et al. [26], urban resilience is comprehended and divided into three fundamental capacities: resistance capacity, absorption capacity, and recovery capacity. The recommendation is to establish urban and engineering networks capable of mitigating flood risk. A similar approach to assessing resilience was proposed by Bruneau et al. [28], introducing the "4Rs" (Robustness, Redundancy, Resourcefulness, and Rapidity). Resilience of specific tools is described by the qualities of the system matching these 4Rs.

These conceptual and (semi)quantitative model methods, grounded in the selection of an appropriate set of indicators, could serve as the cornerstone for creating a framework to evaluate the efficacy of specific mitigation and/or adaptation techniques. Numerous examples of urban catastrophes underscore the ongoing challenges in managing urban flooding, particularly under unstable conditions. Strategic and creative methods are crucial for developing effective urban resilience strategies.

Therefore, it is evident that in risk assessments [29], hazards must be identified, along with the probabilities of their occurrence and a quantification of the effects they would have on vulnerable locations. This facilitates the creation of adaptive management strategies [24].

Application of system dynamics for insurance mechanism analysis

This section delineates the proposed smart insurance mechanism, an outcome derived from previous studies within the Thesis. The novel smart insurance mechanism put forth in the Thesis is tailored for insuring against natural disasters while facilitating insurance companies' active involvement in disaster risk mitigation. This approach signifies a progressive step in the insurance industry's proactive engagement with disaster risk reduction. Given that the issues under investigation are dynamic rather than static, the system dynamics (SD) methodology has been chosen for the analysis of the proposed smart insurance mechanism. The SD approach enables the exploration of the complexity and dynamic challenges associated with the insurance policies under scrutiny. In the Thesis, a case study is conducted using the SD approach, focusing on insurance for local communities in Latvia grappling with the impacts of climate-related disasters on their real estate assets.

The system dynamics methodology was pioneered by J. Forrester and colleagues at the Massachusetts Institute of Technology (MIT) in the 1950s [30]. The SD approach allows the study of different systems with the help of feedback loops, delays, and non-linear relationships between system components. The core tenet of SD is that interactions and feedback between a system's numerous components determine how the system behaves as a whole. See the the key concepts of SD approach in the Thesis.

Numerous disciplines, ranging from corporate management and economics to public policy, environmental studies, and engineering, extensively employ system dynamics modelling. This methodology empowers decision-makers to identify potential obstacles, gain insights into the behaviour of complex systems, and assess policies and tactics before implementation. Understanding the workings of dynamic systems facilitates better planning, decision-making, and problem-solving [31]. System dynamics systems have proven effective in resolving intricate problems within various insurance-related industries, laying a robust foundation for the objectives of this study [32].

The study is elaborated in detail in Publication 1, a review in an open-access journal, and included in the Annex of the Thesis. The development of causal loop diagrams, building stock and flow models, and the validation process is expounded upon in the subsequent sections of this sub-chapter. The analysis of the proposed smart insurance mechanism in a local case study is presented in the results chapter, specifically in Section 2.4.

Development of causal loop diagrams

The initial step in creating the system dynamics (SD) model involves defining the dynamic problem and the model's hypothesis, illustrating the problematic behaviour of the system and proposing a hypothetical solution, respectively. This dynamic problem and hypothesis are most effectively represented by a causal loop diagram (CLD) [30].

Causal loop diagrams (CLDs) illustrate the interaction of variables in the SD model through connections symbolized by arrows. Positive relationships among variables are denoted by a plus sign, while negative relationships are indicated by a minus sign. It is important to note that in CLDs, the connected variables' symbols signify only the change in the link between the two variables, without considering the entire system's change. These connected variables can form loops, known as feedback loops in the SD model. Each type of loop can have a positive or negative impact on other loops in the system:

- Reinforcing loops amplify changes within a system, potentially causing exponential growth or decline and are marked with the letter R in CLD. Reinforcing loops embedded in the system are often the cause of problematic behaviour.
- Balancing loops, marked with the letter B in CLD, have the opposite effect of reinforcing loops. They tend to restore equilibrium or maintain stability within a system due to their counter-interaction with the changes in the initial variable in the loop.

To address the dynamic problem and implement the hypothesis in the SD model, CLDs are constructed based on a review of the literature and expert knowledge of the selected system under study. Once the key variables and their interrelationships are identified in the conceptual model developed with CLDs, the empirical model structure that simulates the system's behaviour is created.

The dynamic problem in this study is defined as follows: existing disaster insurance mechanisms cover the costs of disasters but do not prevent the risk of future damage causes, which are increasing due to the impact of climate change, resulting in an increase in the frequency and intensity of extreme weather events.

The dynamic hypothesis in this study is defined as follows: advanced insurance mechanisms implemented by a smart insurance contract can help reduce damage costs by supporting investment in disaster risk mitigation measures, thus protecting insured assets and, at the same time, attracting new customers due to a more effective insurance scheme.

Building stock and flow model for a local case study

The stock and flow models have been developed to empirically analyse the dynamic problem and implement the hypothesis. Utilizing stock and flow models facilitates the exploration of the dynamic behaviour of a system over time, enabling the identification of key leverage points for policy intervention. To achieve this, the conceptual model derived from CLDs is transformed into a quantitative simulation model using SD software, specifically Stella Architect. This transformation involves establishing the mathematical relationships between the model variables and determining the simulation's time horizon. The requisite data for this case study is obtained from relevant statistics.

For the case study, empirical information was collected for Jelgava, a city in central Latvia with a population of approximately 55,000 people prone to spring floods. The insured assets considered in this study encompass residential buildings facing spring floods with high probability (10 % or once every 10 years), average probability (1 % or once in 100 years), and low probability (0.1 % or once in 1000 years), along with associated losses and restoration costs outlined in Table 1.2.

Table 1.2

Disaster Probability, Damage, and Restoration Costs [33]

Flooding probability in 100 years, %	Flooded buildings area, m^2	Restoration costs per m^2
10 %	103773	19.5
1 %	547400	25.8
0.5 %	695111	31.8

This statistical data serves as input for a stochastic-probabilistic simulation of spring flood hazard events implemented in the SD model through the RANDOM function, incorporating stochastic components and applying hazard probabilities with different return times [34]. The simulation involves a stochastic-probabilistic variable in the model and incorporates random sampling across 1000 simulation runs. This number of simulation runs is deemed sufficient to encompass a variety of potential combinations for disaster event occurrences over a 50-year period, utilizing the provided disaster input data from Table 1.2.

The function describing asset loss is determined based on a damage curve for buildings derived from the national flood risk assessment and management plans. For the insurance model, it is expressed in monetary units (EUR), with the damage defined as the damaged asset area in square meters (m^2). The resulting risk premium that insured assets must pay to the company in the model simulation is estimated for a 10-year period using Eq. (2).

$$RP = L_{\text{average}} + \sigma \cdot P, \tag{2}$$

where:

RP – risk premium;

L_{average} – loss associated with the average yearly loss per asset in the area subjected to disaster;

σ – volatility of yearly loss per asset in the area subjected to disaster;

P – premium charge in %.

Three scenarios are compared with the help of the developed SD model in a simulation for a time period of 50 years and time step of one year. The scenarios are summarized in Table 1.3.

Table 1.3

Analysed Scenarios with the Developed SD Model

Case study scenario	**Name**	**Risk premium**	**DRR measure**	**Flood risk reduction measure efficiency, %**	**Flood risk reduction measure cost, EUR**
1.	Business-as-usual	Assessed every 10 years	No	–	–
2.	Investment in disaster risk reduction	Assessed every 10 years	Riverbed cleaning, coastal erosion prevention, and flow-through restoration	20.5	1 200 000
3.	Smart contract approach	Fixed	Riverbed cleaning, coastal erosion prevention, and flow-through restoration	20.5	1 200 000

The costs incurred by insurance companies, estimated as the total payouts to insured assets after damage has occurred and the return on investment, serve as a basis for comparing the overall costs of transitioning from conventional insurance schemes to smart contracts in the BAU scenario. The comparison involves summing the damage to all assets in the area and the cost of disaster risk reduction measures, based on [33].

The developed SD model enables the simulation of changes in the number of insured assets in the area. The assumption in the case study is an initial share of insured buildings in the area equal to 10 %. In reality, fluctuations in the number of insured assets are influenced by factors such as risk perception and willingness to pay for risk. However, the model does not delve further into the study of risk perception. Changes in the willingness-to-pay-for-risk parameter are subjected to sensitivity analysis to comprehend their influence on the model's output.

Other assumptions in the model concerning the company's profit do not take into account payments for workers and other expenses related to administrative processes. Only risk premium payments are considered as income, with payouts and investment pay-offs as outcomes. The difference between income and outcome is regarded as the insurance company's profit. The study assumes that flood risk reduction measures impact not only the insured assets but also other assets in the area when such measures are implemented.

Testing and validation of the model

Multiple structure verification tests were conducted to validate and verify the developed system dynamics model, encompassing: i) content validation, ii) extreme value test, and iii) sensitivity analysis. The content validation procedure involved a panel of subject-matter experts in climate change, insurance, and system dynamics modelling. During this process, the experts assessed the model's structure, assumptions, and parameters in several stages. Initially, the model's causal loop diagrams (CLDs) were presented to the panel for review, soliciting feedback on the model's structure and assumptions. The panel provided input on key variables and interrelationships, suggesting changes to enhance the accuracy and robustness of the model. Subsequently, the panel reviewed the model parameters, offering feedback on their values and ranges, suggesting changes based on their expert knowledge and available data.

The developed stock and flow model underwent validation through an extreme value test. In this test, the model was calibrated using historical data from the case study and then simulated with extremely high and low parameter values to assess if the model behaviour aligns with the assumptions made in the CLD and SD stock and flow model under extreme conditions. Understanding the effects of uncertainty in data and identifying crucial variables impacting the model's output are crucial for practical model application.

Sensitivity analysis was employed to examine how the system responds to changes in the values of uncertain input parameters crucial for model output. This analysis is essential for assessing the robustness of the model. The results of the extreme value test and sensitivity analysis are elaborated further in Publication 1.

2. RESULTS AND DISCUSSION

This chapter of the Doctoral Thesis presents the main results adhering to the methodological framework of the Thesis. These details are in-depth presented in the ten scientific publications referenced in Introduction.

2.1. Insurance premium calculation methods. Main findings

This section presents the main outcomes in Publications 5, 6, 8, and 10. In particular, key aspects are reported towards insurance premium calculation methods on socio-natural hazards and their potential practical application.

Traditional insurance scheme vs resilience approach

Publication 5 outlines the main characteristics of the so-called *resilience bonds*, highlighting the reference values inherent to the risk that affect the insurance premium, if any, and the uncertainty related and inherent in the contract itself.

In quantitative models for a cost-benefit analysis, considering a traditional insurance scheme and a resilience approach with which we may consider the opportunity of financing mitigative infrastructures. Such aspect are highlighted in the analysis provide by B. G. Reguero [35].

The analysis has to be performed taking account of two viewpoints: one concerning the profit or loss account and the other the balance sheet, to which the mitigative infrastructures must be thought of as an additional value of the asset side. Let us consider that the flood risk could be expressed by the distribution of the claim amount in a fixed time unit, and that this risk must be faced throughout a fixed time horizon, at most even perpetual. Let X be a function with known density function and moments. Let us consider a risk assessment based only on the first two moments thus having $E[X] = m_1$ and $\text{sigma}[X] = m_2$, such that insurance premium P is a function of these two parameters $f(m_1, m_2) = P$. A finite time horizon T (time units) or at least an infinite time horizon can be considered.

Assuming a fixed discount rate r and the relative discount factor $v = 1/r$, the actual total cost for flood risk insurance $C(T)$ can be calculated as reported in Eq. (3):

$$C(T) = \frac{P(1 - v^T)}{r} \tag{3}$$

Then, in the case of infinite time horizon (i.e., perpetual payment), Eq. (4) could be expressed as

$$C(\infty) = \frac{P}{r}. \tag{4}$$

Let us consider a mitigative infrastructure with cost K and a building time duration S. Let us assume $S < T$. Let us consider that after this infrastructure is built, the exposure to flood risk is reduced, i.e., we have a new claim Y with the first two moments $E[Y] = n_1$ and $\text{sigma}[Y] = n_2$, such that insurance premium is a function of these two parameters $f(n_1, n_2) = P_1$ for which it is $P_1 < P$.

A resilience bond is composed of two parts, one relative to the insurance aspect and the other relative to infrastructure financing.

We can assume that for the insurance side the issuer has to pay a coupon equal to P and for the financing side an additional coupon of $Q = g(K)$, till time S, which can be the bond-maturity.

So, the actual total cost in case of a resilience bond approach, defined as function D, over time can be defined as expressed in Eq. (5):

$$D(T) = \frac{(P+Q)(1-v^S)}{r} + \frac{P_1 v^S (1-v^{(T-S)})}{r}. \tag{5}$$

In the case of infinite time horizon (i.e., perpetual payment P_1 after time S), Eq. (6) can be expressed as

$$C(\infty) = \frac{(P+Q)(1-v^S)}{r} + v^S\left(\frac{P_1}{r}\right). \tag{6}$$

Therefore, the total cost for the two approaches, i.e., C and D, can be compared both for a finite and for an infinite time horizon. In this way, conducting a sensitivity analysis on the model parameters, namely X, Y, r, K, and others, is a straightforward task, even including refinement through continual updates with new data.

This allows for a comprehensive understanding of the cost-benefit analysis associated with the utilization of a traditional insurance scheme versus a more robust approach for funding the expenses during the initial time interval until the completion of the mitigative infrastructure, denoted as time S in our scheme. In this context, a resilience bond with a maturity matching the infrastructure timeline and a coupon rate contingent upon the initial risk assessed by premium P, along with the supplementary component tied to infrastructure cost K, emerges as a dual-purpose instrument. This bond serves not only as a means of risk coverage but also as a mechanism for financing the infrastructure eventually including infrastructure for flood risk mitigation.

The final key point is to assess if the higher cost of a resilience bond, with the financing of mitigative infrastructures, could be convenient with respect to a traditional insurance approach, i.e., only facing claims payments, for different time spans.

Risk premium evaluation in the Italian context by exceedance probability

Publication 6 aims to elucidate the dynamics of insurance concerning catastrophic events and how insurance companies engage with insured parties (i.e., contractors) to craft tailored insurance policy contracts. The study mainly focuses on the regulatory landscape in the Italian context, serving as a key example of contractual challenges related to drafting insurance contracts against natural hazards.

Publication 6 identifies the drawbacks arising from information asymmetry between parties, encompassing critical elements of the policy agreement such as the definition of overall risk, exposure, vulnerability, and the consequent insurance premium. A fictional application of exceedance probability (EP) curve for risk and premium assessment by insurance companies is elucidated in Publication 6. This method concentrates on crucial insurance parameters determining the premium and potential indemnity in the context of natural hazard-related risks.

The study introduces the potential connection between insurance dynamics and the new environmental, social, and governance (ESG) parameters for implementation in financial markets.

Publication 6 also focuses on normative aspects. The central theme is a systematic examination of insurance dynamics from the perspective of the company during contract elaboration. This analysis is specifically tailored to the Italian context, with a particular emphasis on the availability of data related to flooding events and extreme weather conditions.

The framework for insurance dynamics against natural hazards, particularly catastrophe models involving the application of exceedance probability, is outlined in the publication. Particularly the second part of the study delves into the dissemination of insurance dynamics in Italy, with a specific focus on natural hazards. This section continues to concentrate on normative studies, elucidating general methods for calculating risk and premiums, and offering an in-depth examination of insurance dynamics from the company's standpoint during contract formulation.

Moreover, Publication 6 highlights how lack of transparency in contractual information poses a significant obstacle, hindering access to data crucial for risk calculations related to assets. Addressing this information gap is crucial for empowering individuals to use the data consciously.

A fictional case study of catastrophe scenarios to an area prone to flood hazards by implementing the curves of average annual losses (AAL) and the probability of exceedance (EP) is outlined in Publication 6. The AAL, also known as 'pure' or 'claims report awards', can be incorporated into pricing alongside allowances for expenses and return on capital. The EP curve is commonly depicted as a graphical representation of the probability that a loss resulting from possible events, such as natural hazards, exceeds a certain amount [30]. Points on the curve offer varying interpretations in terms of the frequency and severity of losses.

These curves are invaluable for insurers and reinsurers in determining the magnitude and distribution of potential losses in their portfolios. The EP curve allows insurers to establish the probable maximum loss (PML) for a portfolio of buildings within a specific timeframe due to the occurrence of a natural hazard. The insurer first defines an acceptable percentage risk and then checks the total loss amount for that specific probability level on the EP curve [36].

Table 1.4

Fictional EP Curve Definition

E_i, step	P_i, %	L_i, €	$EP\ (L_i)$, %	$E\ [L] = p_i\ L_i$, €
1	0.005	1000000	0.00500	5000
2	0.015	750000	0.01993	11250
3	0.02	500000	0.03953	10000
4	0.05	300000	0.08755	15000
5	0.1	200000	0.17880	20000
6	0.2	100000	0.34304	20000
7	0.25	50000	0.50728	12500
8	0.36	10000	0.68466	3600
Total:	**1.00**			**97350**

For the continuation of the discussion, it is crucial to address the theoretical questions described above through a table and a graph. This approach would partially clarify how insurance companies determine risk and pricing based on numerical foundations, specifically in determining the percentage of exceedance probability [32].

In the proposed practical example, it is assumed that there is a set of catastrophic events (E_i) that could pose a threat to the portfolio of immovable assets. Each event has an annual probability of occurrence (p_i) and an associated loss (L_i). Additionally, it is considered that more than one event might occur in the same year. Table 1.4 assumes eight events, ordered by decreasing total losses (L). The sum of the probabilities of all events must equal 1.

The variables included in Table 1.4 could be better explained as follows.

The expected or predicted loss in relation to a given event (E_i) over a timeframe equal to a year is

$$E(L) = p_i \cdot L_i. \tag{7}$$

The total expected losses for the entire set of events, defined as AAL, are given by the weighted sum of expected losses for each event and the probability that the event will occur (see Eq. (8)).

$$AAL = \sum_{i=0}^{n} p_i \cdot L_i \tag{8}$$

If only one event takes place during the year, it is possible to determine the EP curve, i.e., the expressed loss value, as described in Eqs. (9) and (10):

$$EP(L_i) = P(L > L_i) = 1 - P(L > L_i) \tag{9}$$

$$EP(L_i) = 1 - \prod_{i=1}^{n}(1 - p_i) \tag{10}$$

From Eq. (10), it can be deduced that the EP, as shown in Fig. 1.4 in the Thesis.

Furthermore, the weaker party lacks assurance that the scrutiny applied to them, and their assets are reciprocally conducted to the insurance company. The publication highlights the importance of incorporating new parameters, particularly environmental, social, and governance (ESG) criteria [37], into contract and insurance instruments in the Italian context. This inclusion aims to enhance awareness, product safety, and rating reliability while mitigating the information asymmetry prevalent throughout the Thesis methodology.

Many businesses lack comprehensive insurance reserves, impacting the amount of investment capital available. For instance, when examining the division between accrual basis and cash basis in detail, most statistical techniques used for reserve analysis rely on triangles and tables depicting insurance payments over various time periods. While there are numerous statistical methods, they all share a fundamental premise: losses accrued over time follow a consistent pattern.

It is essential to note that there is no additive division of business segments. Instead, when a line of business is subdivided, the same statistical method is applied to each component to estimate results. These individual estimates are then aggregated to estimate the overall line of business. However, this overall estimate rarely aligns with the estimate for the entire line of business obtained using the same statistical methodology. As per convention, the total of the parts of a line of business typically surpasses the reserve estimate made for the entire line of business.

Insurance in the context of flood risk. A multidisciplinary perspective

Publication 8 serves as a pivotal contribution to the implementation of the methodological approach outlined in the Doctoral Thesis. It underscores the imperative need for a multidisciplinary approach when addressing risk, particularly in the context of flood risk mitigation. The publication explores various concepts, including the resilience of critical infrastructure (CI), smart contracts, and blockchain technology. It delves into engineering considerations related to quantifying urban resilience and navigates through legal aspects associated with the integration of smart contracts supported by blockchain technology.

Expanding on the concepts of smart contracts and blockchain introduced in the paper, Publication 8 proposes an innovative actuarial model. This model incorporates a Bayesian adaptive design of the contract, a subject that will be thoroughly examined in Section 3.2. The integration of these cutting-edge technologies not only enhances the understanding of risk but also contributes to the development of more sophisticated and adaptable risk mitigation strategies. The interdisciplinary nature of this research highlights the importance of converging insights from diverse fields to comprehensively address the complexities of risk management, particularly in the domain of flood risk.

Insurance mechanism facing adaptation measures to climate change

Publication 10 explores adaptation measures by insurance companies against climate change, including their proactive investment in risk reduction. It highlights the crucial link between insurers and the annual challenges they face, emphasizing their development of tools in the insurance and reinsurance sectors to tackle natural hazards. The paper classifies these adaptation measures, referencing authors Dlugolecki and Mills. Dlugolecki's classification includes risk reduction, damage control, product price adaptation, and risk transfer. Mills proposes a broader ten-category classification encompassing economic, financial, technical, and policy aspects, with a focus on climate change.

Mills' categories include promoting climate change understanding, building awareness, aligning terms with risk-reducing behaviours, developing new insurance products, investing in climate solutions, and financing customer improvements. These efforts aim to motivate policyholders towards risk reduction and leverage insurance operations for climate change opportunities.

The publication also addresses financial and economic mechanisms in response to natural hazards. It discusses the interplay between private insurance and public interventions, types of risks covered, cost variations, scope of damages, and bureaucratic processes in claiming damages. It notes the importance of financial reserves and different approaches countries take in accumulating these funds.

Finally, the paper emphasizes the significant relationship between natural hazards and insurance companies, the importance of research and adaptation classifications, and critiques the industry for misinformation and financial bias, which excludes many from its benefits.

2.2. Conceptual frameworks towards a new insurance tool. Main findings

Flood risk insurance strategies for public administration

Publication 4 provides a comprehensive analysis of managing flood risk, focusing on the economic and financial aspects and including hydrogeological risks within public administration. The study highlights the responsibility of public administration in mitigating floods and restoring services and infrastructure, such as transportation, energy, water supply systems, and communication networks, affected by such events.

The publication explores three flood risk management strategies: a passive approach (paying for damages as they occur), a conventional insurance scheme, and an innovative resilient insurance scheme. It emphasizes the importance of engineering perspective in quantifying flood risk mitigation and addresses the challenges of implementing these strategies within public administration's regulatory framework. The potential of blockchain technology in enhancing risk analysis and management is also discussed.

The paper examines how climatic phenomena impact different geographical areas and their treatment in the insurance market, including traditional and financial market mechanisms like catastrophe bonds. It notes the significant economic challenge for public administration in upfront investments for adaptation and mitigation solutions.

Focusing on flooding risks, both riverine and coastal, the publication assesses the impact on local assets and infrastructure, considering various factors like territory morphology, hydrogeological risk, population vulnerability, and infrastructure exposure. It introduces a financial scheme for flood risk management, offering choices between different risk reduction strategies, including passive, traditional insurance, and resilient strategies involving upfront investments in hazard-specific mitigation or adaptation projects.

The paper presents a comparative quantitative model for these strategies, employing a stochastic process for future damage prediction and focusing on the role of engineering in risk assessment and infrastructure cost-benefit analysis. The findings contribute to the understanding of system dynamics in flood risk management, emphasizing the importance of assessing the effectiveness of different strategies over time and recognizing the higher initial costs but long-term benefits of resilient strategies. The study also highlights the challenges in linking flood risk to primary sources and the importance of historical damage data in risk assessment in many actuarial models. All subsequent quantities will be treated on an annual basis.

The exposure model can be defined as follows.

Let $X(h)$, i.i.d. for $h = 1, 2, \ldots$, represent the yearly random payment for flood damages in year h, with a distribution function $f(X)$, specifically $f(X) = f(X(h))\ \forall h$, this distribution can be estimated through the analysis of historical series of yearly damages, with moments $E[X^r]$ for $r = 1, 2, \ldots$

Assume that an insurance premium function is based on $f(X)$, denoted as $P = g(f(X))$, where $g\colon \mathbb{R} \rightarrow \mathbb{R}$. According to a standard assumption grounded in risk aversion principles, $P > E[X]$. Full coverage of damages by the insurance contract is assumed.

Suppose that, with a cost W and a completion time n, a mitigative infrastructure alters the random variable describing yearly damages for subsequent years to X_R, such that $E[X_R] < E[X]$ and $\sigma[X_R] < \sigma[X]$. Consequently, for the insurance premium with the same function g, $g(f(X_R)) = P_R < P$.

Assessing risk reduction through engineering expertise could be a challenging task, as it cannot be evaluated using a historical series of damages (given that the mitigative infrastructure did not exist before).

Since the comparison must be made in terms of current values, a generic annual discounting factor v corresponding to the rate of i must be fixed, that is, $v = (1 + i)-1$.

For the passive strategy (indicated with the subscript P in the following symbols), the random present value of the total payment by the public administration, fixed a generic time horizon of m years, $C_P(0, m)$, as reported in Eq. (11),

$$C_P(0,m) = \sum_{h=1}^{m} X_h v^h. \tag{11}$$

The expected value of X corresponds to a deferred annuity installment $E[X]$, expressed in Eq. (12).

$$E[C_P(0,m)] = \frac{1 - v^m}{i} E[X] \tag{12}$$

For the standard insurance strategy (denoted with subscript I in subsequent symbols), the current value of total expenditure for the public administration, deterministic in this case, forms a deferred annuity installment P, as stated in Eq. (13).

$$C_I(0,m) = \frac{1 - v^m}{i} P \tag{13}$$

In accordance with the risk aversion principle, wherein $P > E[X]$, we have:

$$E[C_P(0,m)] < C_I(0,m). \tag{14}$$

However, the passive strategy might incur annual compensation so high as to jeopardize the financial solidity of the public administration. In contrast with the insurance strategy, the public administration can plan a constant yearly payment equal to P. The probability of very high compensation increases with the volatility of X, deducible from the historical series used to estimate its distribution $f(X)$.

The resilient strategy (indicated with subscript R) necessitates payment of insurance coverage P and financing of mitigating infrastructures with cost W for n years. After the completion time, the annual insurance cost decreases to P_R. Let Q be the annual installment for n years to finance the mitigating infrastructure, satisfying Eq. (15).

$$W = \frac{1 - v^n}{i} Q \tag{15}$$

This leads to the total expenditure, deterministic in this case, for the first n years incurred by the public administration, as reported in Eq. (16), and the following chain of inequalities, as presented in Eq. (17).

$$C_R(0,m) = \frac{1 - v^n}{i} (P + Q) \tag{16}$$

$$E[C_P(0,n)] < C_I(0,n) < C_R(0,n) \tag{17}$$

In terms of expected values, in the first n years, the passive strategy (though with a random result) is more cost-effective than the standard insurance strategy, which, in turn, is cheaper than the resilient one. Studying the break-even point problem in terms of time horizon is crucial to determine when the resilient strategy becomes more cost-effective, considering that for a generic value $m > n$, the present (deterministic) value of expenditure overall for this strategy is presented in Eq. (18).

$$C_R(0,m) = \frac{1-v^n}{i}(P+Q) + v^n \frac{1-v^{m-n}}{i} P_R \tag{18}$$

So, the break-even point concerning the standard insurance strategy will be m_I^*, the minimum value of the time horizon m ($> n$) such that

$$m_I^* = \min_{m=n+1,n+2,\dots} C_R(0,m) < C_I(0,m). \tag{19}$$

While the break-even point concerning the passive strategy will be m_P^*, the minimum value of the time horizon m ($< n$) such that

$$m_P^* = \min_{m=n+1,n+2,\dots} C_R(0,m) < E[C_P(0,m)]. \tag{20}$$

Evaluating the cost W and completion time n of the mitigating work and quantifying risk reduction through engineering expertise can be a complicated objective, especially because there is no real feedback on the exposure to risk following the completion of the work. It is necessary to proceed only with hypotheses validated in contexts with some similarity.

A further development, based on such an ability to estimate through engineering skills, could be to evaluate a possible range of mitigating infrastructures, with costs and times given by pairs $W(j)$ and $n(j)$, for the generic j-th option (j = 1, 2, ..., J). From this, the *ex-post* risk exposure distribution is described by the random variable $X_R(j)$ and the corresponding reduced premium $P_R(j)$.

In this case, the problem of optimizing the choice of the mitigating work could concern the minimum $P_R(j)$ given a maximum level of infrastructure cost or the minimum in terms of the break-even point provided by the different choices, i.e., the minimum $m^*(j)$, with $J \in \{1, 2, ..., J\}$.

In comparing the convenience of the different strategies, the role of blockchain tools underlying the concepts of smart contracts would be essential for the need for automatic contract passages from one phase to the next without wasting time, for example, from the completion of the mitigation infrastructure to the certification of risk exposure reduction. A smart contract can be defined as an automatic updating of contractual conditions upon the occurrence of certain conditions to be verified through blockchain tools.

Presenting decision-making problems related to the selection of a risk mitigation strategy becomes intriguing when the distribution of random damage is known. Although no specific reference is made to an actual database of flood-related damage, we adopt a common assumption in the actuarial context, considering a lognormal distribution for random damage.

In particular, the authors aim to emphasize the potential significance of certain parameters in conducting a sensitivity analysis to assess the efficacy of resilient strategies compared to others. This assessment is based on the model introduced in the preceding section.

For the random variable representing damage, denoted as X, we assume a lognormal distribution characterized by parameters μ and σ. We further model the risk reduction after the completion of mitigative infrastructures within a specific timeframe. For the residual risk, X_R, we assume a lognormal distribution with parameters $\mu_R = (1 - d_1)\mu$ and $\sigma_R = (1 - d_2)\sigma$.

The insurance premium loading is hypothesized as a proportion α (> 0) of the volatility associated with random damage. Consequently, the total premium can be expressed as follows.

$$P = E[X] + \alpha\sigma[X] \tag{21}$$

Similarly, for the premium after the completion of the mitigative infrastructure.

$$P_R = E[X_R] + \alpha\sigma[X_R] \tag{22}$$

Considering a standard parameterization characterizing the original risk exposure and one after the construction of the mitigative infrastructure.

$$mu = 1, \sigma = 2, d_1 = 0.1, d_2 = 0.1, \alpha = 0.05 \tag{23}$$

It is important to note that

$$E[X] = 20.08, \sigma[X] = 90.01, \qquad from\, which\, P = 24.58 \tag{24}$$

and

$$E[X_R] = 12.42, \sigma[X_R] = 38.09, \qquad from\, which\, P_R = 14.33. \tag{25}$$

Regarding the mitigation work and its financing (W = 100, n = 5, i = 0.02), from which Q = 21.21 (to be paid over the planned n years of completion time). We proceed with a sensitivity analysis of the break-even points m_I^*, and m_P^*, according to (19) and (20). This analysis examines the time horizon at which the resilient strategy becomes advantageous compared to others, considering variations in the most significant parameters, including the volatility of the original risk and those related to the mitigative infrastructure. Disregarding the description of the volatility of the results and considering them only in terms of their expected values, the standard insurance strategy is consistently less convenient than the passive strategy (see Eq. (21)).

It should be noted that as the volatility of the original risk increases, the break-even point with respect to the standard insurance strategy constantly approaches, but there is no monotonous trend with respect to the passive strategy. The passive strategy's trend depends on the effect of loading the related insurance premium to this parameter, and the cost of the passive strategy, a function of the expected value alone, does not suffer in such a significant way. Of course, the higher the volatility of the original risk, the less safe the passive strategy is, as the probability of huge claims increases, potentially causing serious difficulties to the general economic situation of the public administration.

The results are largely as expected; the break-even point moves away as the cost of the mitigation work increases (see Table 1.5). It could be interesting to analyze a model where, as the cost of mitigation works increases, their effectiveness in terms of risk reduction also increases, leading to a non-monotonous trend in the break-even point. However, a minimum level of abatement may need consideration to avoid making the break-even point the sole decision-making element in measuring the efficiency of the mitigating intervention.

Concerning the sensitivity to the reduction of risk derived from the mitigative infrastructure, we assume that the reduction rates of the parameters describing the original risk, μ and σ, have the same value ($d_1 = d_2$), while the effects of the mitigation works could impact these parameters in various ways, depending on the type of intervention.

It is interesting to note the effect of shortening the break-even point with increasing effectiveness, which is much more pronounced for the passive strategy than the insurance one.

Given the higher cost of the resilient strategy until the completion of the mitigation work, if this period is longer, it also entails an obvious shift in the break-even point, roughly the same magnitude compared to the standard insurance strategy and even more pronounced compared to the passive strategy.

Table 1.5

Break-even Point Sensitivity with Respect to the Volatility of the Original Risk σ, Costs C, Risk Reductions Deriving from Mitigative Infrastructures Measured by $d_1 = d_2$, to Mitigative Infrastructures Completion Time n

σ	m_I^*	m_P^*	W	m_I^*	m_P^*	$d_1 = d_2$	m_I^*	m_P^*	n	m_I^*	m_P^*
2	16	27	100	16	27	0.1	16	27	5	16	27
2.1	13	24	110	17	29	0.11	15	25	6	17	29
2.5	7	22	150	21	36	0.15	13	20	8	19	33
3	6	89	200	26	45	0.2	12	17	10	21	37

Publication 4 introduces an innovative approach that combines the effects of upfront risk reduction investments for public administration with resilient insurance mechanisms. The work presents a multidisciplinary analysis of potential flood risk coping strategies, offering a more comprehensive understanding of hydrogeological risk, an increasingly urgent concern for public administrations, particularly in light of the intensifying manifestations of extreme climatic phenomena in recent years.

The construction of the quantitative model is emphasized to be based on engineering expertise, essential for both ex-ante and *ex-post* risk assessments and for designing the most effective mitigation works in terms of cost–benefit ratio. Given the additional cost of mitigation work, an appropriate indicator for comparing the resilient strategy to others is the break-even point, commonly used in investment evaluation contexts.

Financing for resilience using insurance adaptive schemes coping flooding risk

Publication 7 describes the initial attempt at a basic model for addressing flood risk, involving stakeholder choices (specifically, the public administration responsible for flood risk in a given area) among options such as no insurance, insurance, or insurance combined with investments in mitigative infrastructures.

In this subsection, we do not consider the role of new information collected after the choice time, which could be integrated into contract design. For example, considering trend variations in risk exposure, registered losses, and the comparison between the premium paid and registered losses over time could generate a potential surplus for investment in mitigative infrastructures. This model is refined in publication Publication 7 and utilized to formulate assumptions for the system dynamics model outlined in Sections 2.3 and 2.4.

A multiphase insurance adaptive scheme addressing flood risk in a specific area begins by considering a random variable Y that describes the risk level in the insured area. This variable could represent factors such as rainfall, water levels of rivers, or other indices measuring the primary source of flood risk. Historical series observations (y_i, $i = 1,2...n$) allow us to estimate the distribution of the random variable Y (i.e., $F(Y)$).

Let X be the random variable describing random loss due to flood risk in a fixed unit of time in the insured area without any mitigative infrastructures. Historical series observations (x_i, with $i = 1,2...n$) allow us to estimate the distribution of the random variable X (i.e., $F(X)$). Applying a premium principle based on the distribution of X enables us to determine a premium $P[X]$ per unit of time.

The insurance contractual conditions need to consider estimates related to the random variable X. It could be valuable to estimate a regression model between X and Y, directly linking contractual conditions to the original source of risk, especially in cases of data scarcity for losses. Hydraulic engineering expertise could help estimate the regression function between X and Y when various mitigative infrastructures are built.

Assuming C_i, with $i = 1,2...m$, as an increasing sequence of infrastructure costs, we can determine the regression functions li (with $i = 1,2...m$), describing decreasing risk exposure given the distribution of Y. So, let $P[Xi]$, $i = 1,2...m$, be the premium per unit of time if infrastructure i is built. From the assumption of the efficiency of mitigative infrastructures, we have $P[X_i] < P[X_{i+1}]$ for each i. If t_i is the time necessary to build up infrastructure i, let us assume that before the infrastructure is finished, the risk exposure remains the original one. Although a more detailed assumption about the evolution of risk exposure during the building time can be considered, we prefer to focus on a simplified version.

Let l be the regression function between X and Y without any mitigative infrastructures $X = l(Y)$. The fundamental choices for stakeholders, such as public administrations responsible for flood risk, include: no insurance (and no resilience action), paying random losses (average E[X] for each unit of time).

1. No insurance, taking resilience action through mitigative infrastructure i, and paying random losses (average $E[X]$ for each unit of time) plus the constant amount c_i / t_i.
2. Insurance and no resilience action, paying a constant amount $P[X]$.
3. Insurance and resilience action through mitigative infrastructures i, paying a constant amount $P[X] + c_i / t_i$ until time t_i; after that, the premium $P[X_i] < P[X]$ for each unit of time.

Considering there are m possible infrastructures, strategies II and IV have m different scenarios. The comparison between I and III depends on the randomness of future losses relative to the average value estimated for the past. A similar comparison can be made between II and IV, but since we do not have observations of the losses relative to r.v. Xi (for each $i = 1,2\ldots m$) due to historical series not considering risk mitigation by infrastructures i, estimation relative to r.v. X_i is based solely on engineering expertise. Thus, the authors focus on the crucial choice between III (average is the same as I) and IV (average is the same as II) for each infrastructure i, with $i = 1,2\ldots m$, choosing between no resilience and resilience. The present value (PV) of the total cost, with a discount rate r, is considered for a fixed time T, leading to the following expressions:

$$PV(III) = \sum_{j=1}^{T} P[X](1+r)^{-t_j}\,; \tag{26}$$

$$PV(IV,i) = \sum_{j=1}^{i} \left(P[X] + \frac{c_i}{t_i}\right)(1+r)^{-t_j} + \sum_{j=i+1}^{T} P[X_i](1+r)^{-t_j} \tag{27}$$

In the given scenario outlined in the preceding subsection, let us consider a regular time grid s_i, where $i = 0,1,2,\ldots,k$, at which we reset the insurance contract accordingly. We initiate the process without any infrastructure, relying on engineering expertise estimations of infrastructure costs and their associated risk reduction effects. If P represents the constant total premium paid from s_i to s_{i+1} (with $I = 0,1,2,\ldots,k{-}1$), and $X\,(i,\ i + 1)$ denotes the total loss incurred in the same interval, two distinct cases emerge. In the first case, $\mathrm{P} < X\,(i,\ i + 1)$, and in such instances, the insurance system covers the larger losses. Conversely, in the second case where there's a surplus $P < X\,(i,\ i + 1)$, the adaptive contract design may allocate a portion of it, denoted by a in the range (0,1), back to the insured.

These surpluses are aggregated, and the insured, typically the public administration, then has the choice of which kind of infrastructure to invest in. If the decision is to invest in infrastructure i, the stakeholder must wait to accumulate a total surplus equal to its cost, c_i. At the designated time, according to the regular grid introduced earlier, a new contract begins. The premium paid by the insured must be estimated using information collected up to that time for a contract of further duration t_i, representing the time necessary to build up infrastructure i. Following this additional duration, the insurance contract proceeds with a premium $E[X_i]$, considering the expected loss associated with infrastructure i.

It is worth noting that with this adaptive model, the starting premium P must be higher than the expected loss since it needs to generate the surplus required to finance the mitigative infrastructure. Only when the necessary surplus has been raised, does the insurance premium becomes fair relative to expected losses. This design with a fixed premium and surplus distribution aligns with the legal framework of smart contracts. The new definition of the premium requires a renegotiation between the two counterparts, as stipulated by the same legal environment. The optimization problem in this adaptive insurance scheme aims to determine the strategy that minimizes the total cost, as discussed in the preceding subsection. The optimal strategy is defined in terms of the pair P and infrastructure i. It is crucial to compare equivalent strategies, such as no insurance or only insurance (without resilience), within this optimization problem. The total cost for the strategy (P^*, i^*) is expressed as follows:

$$PV(P^*, i^*) = \sum_{j=1}^{i} P(1+r)^{-s_j} + \sum_{j=i+1}^{i+ti} P[X](1+r)^{-t_j} + \sum_{j=i+ti+1}^{T} P[X_i](1+r)^{-t_j}, \tag{28}$$

where s_i represents the expected time at which the necessary surplus c_i is collected.

This formulation captures the core of the optimization problem within the adaptive insurance scheme. It takes into account not only premiums, surpluses, and infrastructure costs over time but also delves into the identification of potential strategies for insurance companies. One such strategy involves allocating a portion of the surpluses to bolster investments in disaster risk reduction (DRR) strategies. This, in turn, aims to raise awareness and encourage increased insurance coverage for both assets and civilians.

Flood risk insurance. From blockchain to a Bayesian adaptive design contract

Publication 8 introduces an adaptive Bayesian insurance contract designed for managing flood risks in a multi-periodic scenario, integrating actuarial, engineering, and legal disciplines. The paper emphasizes the use of blockchain technology for smart contract frameworks, allowing for the seamless integration of new reliable information into risk management.

The publication explores the combination of smart contracting and blockchain technology with Bayesian adaptive design in flood risk insurance. It highlights the importance of quantitative tools for urban resilience assessment, big data processing from GIS and satellite monitoring, and the need for resilient insurance mechanisms with flexible contracting options like smart contracts.

The increasing urban population and consequent exposure to flood risks necessitate multidisciplinary approaches in research. Critical infrastructures (CI), including energy, water, transport, banking, and ICT systems, are identified as assets at heightened risk due to urban complexity and land constraints in high-risk areas. The paper calls for innovative risk management frameworks that address climate change effects and natural hazards, incorporating both engineering and societal considerations.

Publication 8 acknowledges the difficulty in assessing individual infrastructure or asset risks due to data scarcity, leading insurance companies to use proxies. It advocates for a holistic risk reduction approach, incorporating social, environmental, financial, and political systems to enhance overall resilience. The paper emphasizes the spatial and time-dependent aspects of flood risk preparation, resistance, and adaptation, highlighting the role of advancing computing and big data processing technologies.

The publication stresses the importance of improving flood risk assessment by enhancing programming device capabilities to process diverse datasets, advocating for a multidisciplinary approach involving GIS, probabilistic modelling, and damage curve definitions. Blockchain technology is presented as a solution for real-time risk assessment and precise insurance policy pricing.

Blockchain is defined as a decentralized ledger and transaction system, functioning beyond payment and exchange, acting as an international safe register shared by a network, eliminating central repositories. Smart contracts are introduced as IT protocols that formalize agreement elements and execute predefined terms automatically.

Smart contracts' rapid development is noted, with applications ranging from financial derivatives to online goods sales without central authorities. The paper explores the insurance sector's dynamics with blockchain, highlighting innovative insurance forms using smart contracts, such as Insure ETH and a pilot project by AIG, IBM, and Chartered Bank.

A significant gap is identified in the transition from a refund-based to a big data management approach in insurance, enabling multi-period contracts through blockchain technology and external data sources. This approach allows for contract elements to be periodically modified, offering adaptability in natural disaster contexts.

The paper differentiates between a one-dimensional perspective, where blockchain verifies insured events, and a multi-dimensional perspective, where blockchain perpetuates and modifies contracts over time. In this multi-dimensional approach, blockchain securely stores relevant insurance data, facilitating the continual modification of contract parameters based on data flow and mutual consent.

Building upon the concepts of smart contracts and blockchain introduced in Publication 8, an actuarial model with a Bayesian adaptive design for the contract is proposed. Consider the set of data, denoted as $H(0)$, representing information collected at time 0, originating from time $-m$. Let function W represent the premium to be paid for one unit of time until the first updating time, as detailed below.

$$W(0) = f(H(-m, 0) \equiv f(H(0)) \tag{29}$$

Within this dataset, we include information on damages resulting from the insured risk. Additionally, the dataset encompasses relevant details related to flood risk, mitigative infrastructures, and other pertinent factors. This information plays a crucial role in the comprehensive analysis and understanding of the risk landscape, allowing for a more nuanced evaluation of the effectiveness of mitigative measures and the overall resilience of the system in the face of potential hazards. The inclusion of these diverse data points facilitates a holistic examination of the complex interplay between insured risks and various contributing factors, contributing to a more robust and informed risk assessment framework.

Consider the sequence of updating times in the contract denoted as m_1, m_2, and so forth (i.e., m_i). At any given time, m_i, where i takes values from $1, 2,$ and beyond, the updated premium is determined by leveraging the information collected starting from $-m$, denoted as $H(-m, m_i)$. The calculation for the new premium that must be paid until the updating time m_{i+1} is defined by Eq. (30) as follows:

$$W(i) = f(H(-m, m_i) \equiv f\big(H(i)\big). \tag{30}$$

Let us assume that the collected information $H(0)$ comprises the historical series of damages, denoted as $x(i)$, where i takes values from $-m$ to 0 (i.e., $i = -m; -m + 1, \dots 0$), representing each time unit from $-m$ to the issue date 0 (see Eq. (31)).

$$H(-m, 0) = x(-m), x(-m + 1), \dots x(-1), x(0) \tag{31}$$

Let us assume $H_r(0)$, where $r = 1, 2, \dots$, represents the estimate of the r-th moments of this random variable. If we adopt a premium principle based on a variance-style charge, our interest lies solely in $H_1(0)$, $H_2(0)$, and so on. The premium for a time unit starting from the issue date, denoted as $W(0)$, can be expressed as outlined in Eq. (32).

$$W(0) = f(K_1(0), K_2(0)) \tag{32}$$

Commencing from the issue date, the contract entails payments of the premium $W(0)$ for each unit of time until the first contract update at time m_1, triggered by the arrival of new information denoted as $H(1, m_1) = x(1); x(2)\ldots x(m_1)$.

At time m_1, leveraging all the information recorded in the interval $(-m, m_1)$, new estimates for $H_1(m_1)$ and $H_2(m_1)$ are obtained. Consequently, the premium is updated as articulated in Eq. (33).

$$W(m_1) = f(K_1(m_1), K_2(m_1)) \tag{33}$$

This premium must be paid for each time unit from $m_1 + 1$ to the next updating time m_2.

Now, let $n_i = m_i - m_{i-1}$, where i takes values from 1, 2, and so forth, representing the number of time units between m_i and m_{i-1}. Consequently, the total premium paid in such an interval is $n_iW(i)$. The disparity between this total premium and the total claim in the same time interval, denoted as $C(i)$, is expressed in Eq. (34).

$$n_iW(i) - C(i) = U(i) \tag{34}$$

This represents either a profit or a loss for the insurance company. The contract may stipulate that in the case of a profit, i.e., when $U(i)$ is positive, a portion of the surplus earned by the company will be shared with the insured. This sharing can take the form of infrastructural investments aimed at risk mitigation. The assessment of the costs associated with mitigative infrastructures and their impact in terms of risk reduction requires an engineering analysis, as previously described.

The influence of infrastructural investment on this numerical model can be introduced through a non-decreasing sequence of thresholds, denoted as $L(i)$, where I takes values from 1, 2, and so forth in the interval (m_{i-1}, m_i). These thresholds affect damages during the same time period: the higher $L(i)$, the lower the expected total damage $C(i)$.

The assessment of the relationship between surplus and threshold increase needs to be carried out using engineering considerations. It is reasonable to account for a delay between the emergence of the surplus and its impact on the threshold, owing to the time required to complete the infrastructure.

The role of blockchain technology lies in certifying the collected information and automating the changes in contractual terms (i.e., the premium level and surplus sharing) at each updating time. This automation is central to the concept of smart contracting, involving the update of the contract without a new negotiation between the two parties. This approach has been of paramount importance for implementation in the system dynamics model, as presented in Section 2.4, and aligns with the principles outlined in Publication 1.

Publication 8 explores the integration of blockchain technology in the insurance industry, focusing on its application in Europe, particularly Italy. The paper references the Fizzy Axa contract as an example of blockchain's potential in creating efficient, real-time data flow within insurance contracts. It discusses the relevance of this technology to public administrations, emphasizing the importance of evaluating investments in mitigation and the potential reduction in risk coverage costs.

The publication stresses the need for a European platform to transfer described risks to financial markets, highlighting the importance of legislative harmony within the European context. This alignment with supranational treaties and the Covenant of Mayors is crucial to avoid fragmented national regulations. Further, the paper delves into the applicability of the proposed premium risk calculation in developing quantitative infrastructure resilience models. This approach is crucial for making informed political, business, and financial decisions, particularly in the realm of mitigation structures and resilience bonds. The viability of funding mitigation infrastructures through resilience bonds, as opposed to conventional insurance methods that primarily cover claims, is a focal point of discussion.

Publication 8 also addresses the strategic planning challenges in insurance organizations, advocating for the use of diverse analytical methods like break-even analysis and income stability assessment. These methods are vital in addressing information asymmetries in insurance contracts and monitoring key success factors for financial and economic development. The examination of insurance portfolios is critical for strategic planning, ensuring financial stability and solvency. The paper underscores the complexities insurance companies face in determining client premiums, influenced by risk ambiguity, moral hazard, and other uncertainties. The demand for catastrophic insurance is affected by various factors including income levels, risk knowledge, and expectations of post-disaster public reimbursement. Cultural, behavioral, and educational factors also influence insurance demand, which is not solely based on the logical trade-off between policy price and benefits. A robust institutional framework and clear regulations are essential for competitive insurance market growth.

Publication 8 highlights the potential for contracts to automatically update, including aspects related to risk mitigation infrastructures, with blockchain technology facilitating this process. The paper concludes by suggesting future research directions, emphasizing the need for a collaborative dialogue between engineering and actuarial fields, and legal perspectives to ensure the effective application of smart contracts in multiperiodic scenarios.

Multi-disciplinary approach in insurance contracts coping with natural hazards

Publication 9 addresses the critical role of risk insurance in socio-natural disaster management, highlighting its importance in pre-disaster risk reduction strategies to alleviate financial burdens post-disaster. It identifies a gap in integrating risk insurance strategies for community resilience planning, emphasizing the need for a holistic approach that includes pre-disaster mitigation measures and risk prevention strategies.

The paper stresses the significance of insurance markets in mitigating economic impacts of natural and climate change disasters. It calls for more precise quantification of the benefits and costs of engineering-based mitigation solutions and a robust legal framework for implementing an actuarial quantitative model. This approach should integrate multidisciplinary perspectives, utilizing platforms like blockchain technology for information collection and processing.

A key focus is on the application of blockchain technology in natural disaster risk insurance contracts, proposing a multidisciplinary methodology to develop digital insurance contracts on a blockchain platform. This method aims to enhance catastrophe risk insurance's impact on community resilience, considering pre-disaster conditions.

The paper discusses the role of governments and legal entities in insurance, particularly flood insurance, which is closely linked to land planning and adaptation investments. Given the rise in economic losses from disasters, especially non-insured losses due to climate change, there is an urgent need for precise risk assessments using extensive data processing. This approach includes leveraging big data for optimal insurance premium pricing, enhancing community resilience, and strategically allocating resources. Blockchain technology's potential in the insurance sector is explored, with its feasibility in instant insurance and its increasing exploration by the insurance industry for applications like peer-to-peer insurance and reinsurance. However, current models still depend on traditional insurance structures, with smart contracts being an emerging innovation.

Publication 9 highlights the development of insurance-based mechanisms for adaptation, contributing to local resilience against disasters. Blockchain technology is seen as a robust platform for mitigating risk and vulnerability through diverse data sources, enabling real-time risk assessment and more precise insurance policy pricing.

The paper identifies a gap in implementation, pointing toward a transition from refund-focused insurance blockchains to ones centered on big data management. The future may involve a shift toward multi-phase contracts, involving periodic data scanning for contract evolution and adaptation. The paper suggests features for a multi-phase contract, including onerousness, randomness, IT stipulation using blockchain, real-time data flow, and automatic renegotiation. These features can create a valuable information network against risk phenomena, involving the modification of initial contract parameters based on mutual consent.

Finally, the paper proposes a methodological approach that integrates engineering, insurance-actuarial, legal, and IT dimensions within a blockchain-supported platform, aiming to optimize regulatory, insurance, and engineering interactions for natural hazard risk reduction strategies.

In summary, Publication 9 presents a comprehensive approach that integrates various scientific areas, leveraging blockchain to enhance risk reduction, resilience, and optimized insurance practices. Within this definition, a customized blockchain platform for ‘community’ risks is proposed for environmental risks in specific geographical areas. This involves disciplines such as engineering (estimating accident probabilities, designing risk mitigation tools, and assessing potential damage), legal (legislation for public-private synergies and supervising the digital platform), actuarial (quantifying bonuses for potential damage coverage transfer), and IT (establishing a blockchain-based digital platform) (see Fig. 2.1).

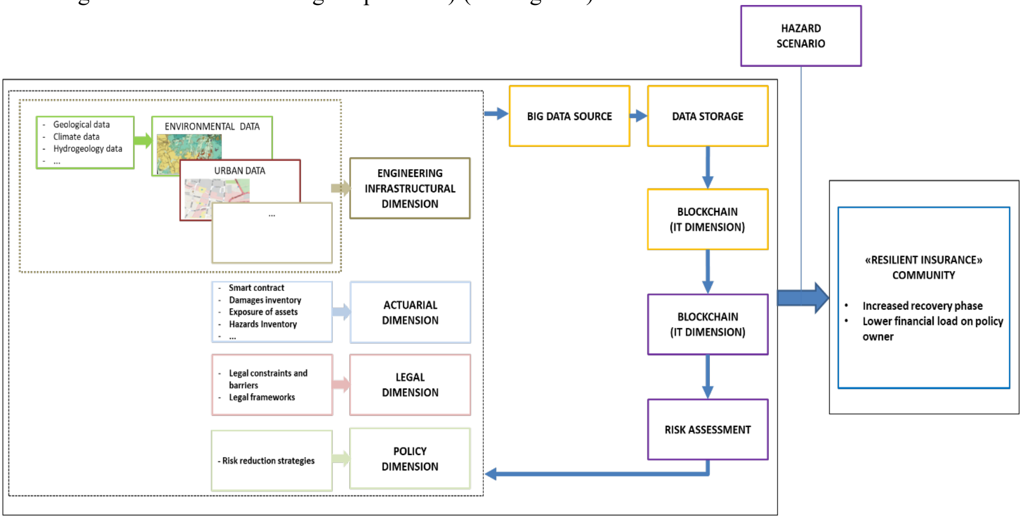

Fig. 2.1. Novel multi-disciplinary approach for blockchain implementation.

2.3. Case studies

Insurance mechanism for cultural heritage with adjusted gross revenue

Natural hazards, exacerbated by climate change, are increasingly damaging cultural heritage. The rise in frequency and economic impact of natural disasters has spurred the development of insurance tools as risk management strategies. However, in Italy, individual assets are often underinsured against disasters, while a limited number of public entities and small to medium-sized companies have specific policies for earthquakes and floods. A slight increase in insurance uptake by larger companies has been noted recently. The low penetration of insurance among individuals is attributed to the 'disaster syndrome', characterized by shock and bewilderment during disasters, leading to demand-side distortions and inadequate disaster resource supply.

In Italy, a country with numerous socio-natural hazards, COVID-19 impact on cultural heritage was significant. Measures included closing museums and cultural sites, severely impacting income from these activities. Disaster prevention and post-disaster management are crucial for protecting cultural heritage. The Italian experience with the Department of Civil Protection and the Ministry of Civil Protection, involving the development of behavioural models by trained teams' post-earthquake, is considered effective. These models help describe damage, calculate vulnerability, and estimate intervention costs.

Preventive measures for hazards can be structural or non-structural, but structural measures are challenging for cultural heritage due to visibility, disturbance, and cost-effectiveness. Publication 2 focuses on innovative strategies for pre- and post-disaster risk mitigation for economic heritages, particularly those vulnerable to disasters like the COVID-19 pandemic. The study highlights the financial impact of COVID-19 on Villa D'Este and Villa Adriana in Tivoli, Rome, significant UNESCO-designated cultural sites. These sites, initially designated separately, boast numerous fountains, nymphaea, grottoes, and water themes.

Economic risk assessment for cultural assets, like Villa Adriana and Villa D'Este, should consider various disaster types, including environmental, seismic, fire, or health-related. Different hazards affect revenue and expenditure differently. The Italian context illustrates pandemic impacts on ticket sales. The paper is part of a broader research on biological hazards and cultural heritage, detailing the losses of Villa Adriana and Villa D'Es*te* during the pandemic. Unlike a pandemic, a fire or flood would lead to temporary closure and restoration costs, impacting ticket sales. Assessing these effects requires engineering-structural analyses and considering insurance coverage as a flexible cost component based on ongoing claims experience. The next part of the study proposes a case study, starting with premium quantification using a flexible insurance approach.

Consider a random variable X that describes the theoretical amount of compensation in the time unit (for example, one year), from which an insurance premium P can be calculated. In traditional insurance, this premium is considered constant for each period of coverage and is a function of the distribution of X. The variable X encompasses all damages [11].

The flexible approach involves recording the suitable compensation amount during the period preceding a recalculation and redefinition date (t) from the inception (start) of the insurance coverage, which can be fixed as time 0, representing the compensation for t years, denoted as $Y(0,t)$. The frequency of recalculation must be contractually determined and outlined annually or at a different specified frequency.

Let $Y(0,t)$ represent the total amount compensated by the insurance company and P denote the sum of premiums paid by the insured within the same time frame. The flexibility lies in providing a *bonus-malus* scheme based on different predefined levels, as described in Eq. (35):

$$Y(0,t) - P = D(t) \tag{35}$$

Should $D(t)$ exceed a certain threshold, meaning more compensation than premiums paid, the flexibility scheme might increase the premium until the next recalculation. On the other hand, if $D(t)$ is negative, there could be a decrease in the premium sum until the next recalculation or retrocession of part of $D(t)$ to the insured party, perhaps to be linked to risk mitigation works. More specifically, the potential progression of risk mitigation works, to be financed independently and/or through these hypothetical insurance retrocessions, may gradually decrease the total amount of insurance coverage, provided that the sum of the actual and effective damage is positively affected (i.e., reduced) by mitigation; otherwise, this flexibility scheme would end up generating positive $D(t)$ levels, consequently increasing the premium.

This section presents a real case study based on the methodology and calculation methods aligned with the Doctoral Thesis and Publication 2. As highlighted earlier, cultural heritage has traditionally been considered a static element whose value is represented by the intrinsic value of the assets that compose it and the cost of reconstruction. Over time, companies have adopted traditional forms of risk mitigation and reconstruction insurance without the desirable diffusion for such a decisive and important issue for public welfare. Initially, insurance coverage focused on ex-post protection, involving the disbursement of equal sums, theoretically for the reconstruction of damaged assets. More recently, attempts have been made to provide ex-ante protection, allowing the constant disbursement of the insurance premium to allocate part of it to the construction of risk mitigation structures.

The author's idea in the possible development of a different approach lies in the notion that economic cultural heritages can no longer be understood solely as public assets whose value is outlined by the cost of the immovable asset itself. Cultural heritage, exemplified by Villa D'Este and Villa Adriana, must be considered economic activities and industries exposed to the risk of natural hazards and business risk. Public entities, while not subject to insolvency rules, are susceptible to market rules and fluctuations in cash flow. Unravelling doubts about the systematic classification of economic cultural heritage as public industries, it seems appropriate to assess whether some form of insurance, initially used for other areas, could be useful for heritage when incomes are affected due to hazards, losses, and negative fluctuations.

To mitigate the catastrophe risk from natural hazards regarding financial losses, the author suggests evaluating the option of adopting a particular form of insurance, widespread, above all, in the USA in the agricultural field – protection derived from the adjusted gross revenue (AGR). AGR insurance is a non-traditional insurance plan that allows the risk management of the entire company. It is a compelling product that could serve as a model for possible application in Italy and other European Union countries. AGR is a policy that insures company revenues, using the historical gross revenues of an agricultural company as a reference parameter, obtainable from tax data (average of the last 5 years) reported by the parties. This insurance product is applicable to any production sector.

Although closely related to the paper, the AGR policy offers, among other features, insurance coverage for losses of gross revenues due to natural disasters or calamities. Using the data obtained from the paper on the calculation of the COVID-19 losses for the heritage of Villa D'Este and Villa Adriana, the following calculations are reported after proceeding to the calculation table for the elaboration of the insurance premium and respective disbursement.

The data inventory necessary to calculate the AGR for the presentation of the case study are presented clearly in the full manuscript with a reference to years 2017–2019 (i.e., before COVID-19).

The value is verified by the approved insurance provider (AIP), which then utilizes it to calculate the insurance coverage. The insurance program offers different levels of income coverage. The insured individual may choose the package that best suits their needs. The packages offered include:

- 80/75 or 80/90 = coverage level of 80 % with the payment of a rate of 75 % or 90 %;
- 75/75 or 75/90 = coverage level of 75 % with the payment of a rate of 75 % or 90 %;
- 65/75 or 65/90 = coverage level of 65 % with the payment of a rate of 75 % or 90 %.

Publication 2 envisages the introduction of an insurance policy known as agricultural risk insurance. The study strongly advocates for the implementation of AGR, highlighting its potential benefits in curbing macroeconomic and financial repercussions, minimizing losses, and mitigating risks associated with natural calamities.

To function effectively, insurance programs must accurately quantify risks and provide comprehensive coverage. A deep understanding of socio-natural hazards is essential for creating effective mitigation strategies to protect urban cultural heritage. This approach reduces macroeconomic impacts and risks from natural hazards, aligning with resilience and risk management strategies. The introduction of adjusted gross revenue (AGR) can improve insurance market dynamics and mitigate hazard consequences by limiting costs and financial damage. AGR also enhances economic resilience against natural disasters, providing a financial safety net and reducing economic fallout, fostering a culture of preparedness and long-term resilience in the insurance industry and the broader economy.

Socio-natural disaster effect in cultural heritage during COVID-19. Losses estimation

Publication 3 focuses on cultural heritage at risk from socio-natural hazards, highlighting irreversible damage from climate effects and disasters. The European Parliament notes that such impacts can destroy cultural heritage, including movable and immovable elements. The study examines the financial impact of COVID-19 on Villa D'Este and Villa Adriana in Tivoli, Rome, chosen for their significant income loss and UNESCO recognition. Their selection was based on their international importance, management methods, availability of financial data from 2017–2020, and the severe economic impact of COVID-19 in their location. The study includes tables analyzing budget items and the negative impact of hazards. It emphasizes the need for economic risk assessment for cultural assets, considering cost reductions and multi-hazard scenarios like extreme weather or pandemics, using historical data to estimate economic risks to various balance sheet items in catastrophic scenarios.

Based on the investigated case study, the reduction in ticket revenue during catastrophic events can be evaluated. Utilizing the daily average of incomes, b, (assuming a constant flow without seasonality) from previous years, derived from annual total receipts $B(t)$ with t = 2019, 2018, ..., and considering m annual revenue figures, the following descriptive equation can be derived.

$$b = (B(2019) + B(2018) + \cdots + B(2019 - m + 1)) \cdot \left(\frac{1}{m}\right) \cdot \left(\frac{1}{365}\right) \tag{40}$$

Based on the equation the impact of a forced lockdown, such as the one in 2020 due to the pandemic could be assessed and the estimate of the reduction in collection with the years before (i.e., 2017–2019) could be compared. To illustrate this with a numerical example using the data for collections in 2017–2019, it can be determined that

$$b = (3350822 + 4000000 + 4869535) \cdot \left(\frac{1}{3}\right) \cdot \left(\frac{1}{365}\right) = 11.160. \tag{41}$$

Then, assuming a forced lockdown of n = 130 days in 2020, there would be an estimated loss of €1 450 818, which is then compared with the difference between the average takings in 2017–2019 (€ 4 073 452) and the total ticketing income in 2020.

Publication 3 underscores the vulnerability and economic instability of cultural sites, exemplified by the impact of the COVID-19 pandemic on cash flow in 2020. The simple mathematical equations calculate the average income losses, considering the three-year period (2017–2019) as the baseline and factoring in the days the site was closed.

Key findings include the disproportionately high management costs of cultural sites, even when closed, the exposure to risks without effective mitigation measures, and the lack of insurance coverage in financial records related to natural events. Additionally, the study emphasizes the following aspects:

- Public administrations, including the examined cultural heritage, are exposed to hazards without adequate preventive and remedial countermeasures. The hazard of COVID-19 revealed a lack of measures despite not causing direct damage to assets and people.
- The second key aspect concerns the inconsistency of provisional balance sheets drawn up before the pandemic outbreak and the inability, both generally and specifically, to address it at an entrepreneurial level.
- The third aspect highlights the total absence, as per balance sheets, of any insurance coverage related to natural events, emphasizing the need for insurance that maintains the flow of money to avoid worsening direct and indirect consequences.

2.4. Smart insurance mechanism analysis by system dynamics approach

The functioning of the insurance mechanism studied and implemented in the system dynamics (SD) model for the defined case study is best elucidated through causal loop diagrams (CLDs). The conceptual model, developed with CLDs for three case study scenarios, identifies the key variables and their interrelationships within the studied system. By employing reinforcing and balancing loops in CLDs, the conceptual model introduces a dynamic problem of the system and a dynamic hypothesis of the model. This is based on a thorough review of the literature and the expert knowledge of the selected system under study.

The simulation results of the stock and flow model, which is based on CLDs and delineates three case study scenarios, are analysed by comparing model variables such as risk premium, area of assets insured, insurance company profit, insurance companies' expenditure, and total costs of disaster. These variable results facilitate a comprehensive comparison of different aspects of the performance of the proposed smart insurance mechanism in the analysed scenarios. A more detailed analysis of the results is available in Publication 1.

Scenario 1 model

The problem explored in case study Scenario 1 revolves around the notion that in a business-as-usual insurance mechanism the total risk premium payments escalate with an increased number of insurance contracts due to heightened risk perceptions linked to climate change. The hypothetical behavior in this scenario is depicted in Fig. 2.2, illustrating risk premium payments and insurance payout flows over a 10-year period.

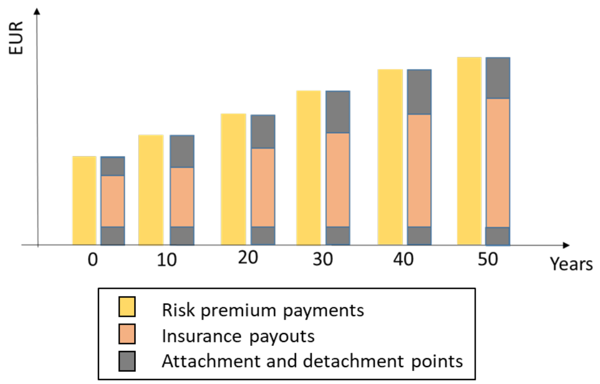

Fig. 2.2. Illustration of insurance companies' payment flows in case study Scenario 1.

The attachment point signifies the loss level at which the insurance company intervenes to cover excess losses, while the detachment point indicates the loss level at which the insurance company ceases coverage. The sum between the attachment and detachment points of insurance is utilized for payouts to insured assets, indicating that the risk associated with these points is not covered.

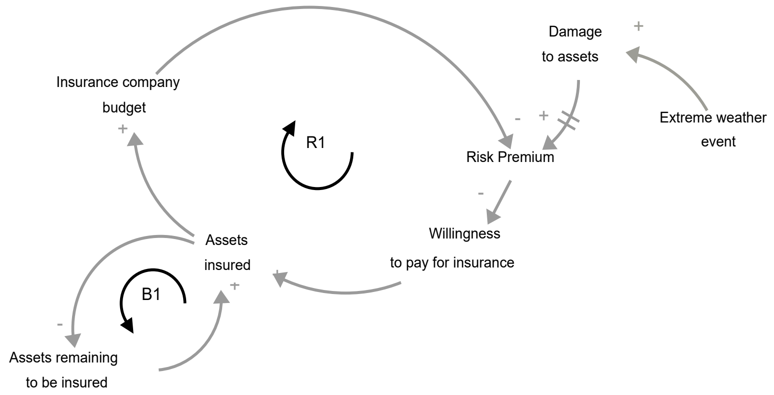

Fig. 2.3. CLD for case study Scenario 1.

For case study Scenario 1, a causal loop diagram (CLD) is formulated and presented in Fig. 2.3. The main components of the CLD are two feedback loops and variables: damage to assets and extreme weather events. The relationships between the variables suggest that assuming all other factors remain constant, an increase in the extreme weather event variable will lead to a rise in the value of damaged assets. Similarly, a surge in asset damage will result in an increase in the cost of risk premiums after the reassessment of risk premiums in contracts within a 10-year period. The time delay between accounted damage to assets over the period for which the risk premium is assessed is represented by the two stripes on the connector between damage to assets and risk premium.

Risk premium, willingness to pay for insurance, assets insured, and insurance company budget are the variables linked in the reinforcing loop R1. The values of the variables related to the reinforcing loop R1 increase in a closed loop, following the reinforcing loop definition. This loop illustrates the dynamic issue of the rising risk premium over time due to increasing asset damage, resulting in rising insurance company budgets and a subsequent decline in the risk premium, as seen in Fig. 2.2. In this case, the supply-demand elasticity function determines the extent to which the risk premium value will decline. The number of assets in the area determines the growth of loop

R1, and the CLD is complemented by balancing loop B1, which includes variables 'assets insured' and 'assets remaining to be insured'. The empirical model structure, known as a stock and flow model, simulates the system's behavior based on developed CLDs. The results of the empirical model simulation for case study Scenario 1 are presented and discussed more comprehensively in Publication 1.

Scenario 2 model

In accordance with the approaches outlined in Scenarios 2 and 3, the government would invest in disaster risk reduction (DRR), thereby enhancing the safety of the covered assets. The underlying concept of these scenarios is that the insurance firm takes on the responsibility to reimburse the government's investment through bonds, thereby positioning the insurance industry proactively as a driver for risk reduction and preventive measures.

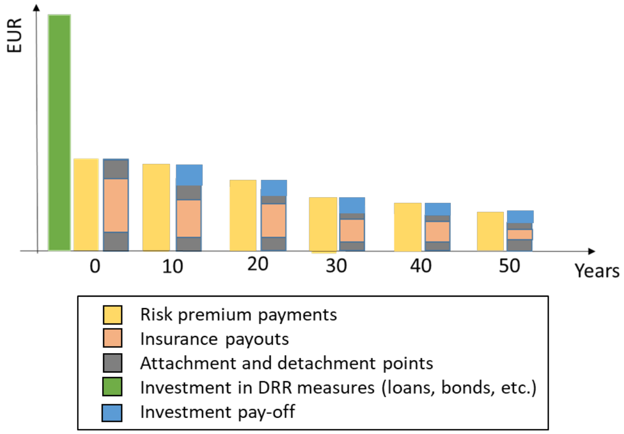

Fig. 2.4. Illustration of insurance companies' payment flows with investment in disaster risk reduction (Scenario 2) [38].

The government is envisaged as the local area's representative responsible for DRR development, thereby expressing interest in progressing towards investment in DRR, ultimately repaid by the insurance firm through bonds. This strategy assumes that effective DRR implementation will lead to a reduction in risk, subsequently resulting in diminished insurance payouts due to fewer incidents causing asset damage. Scenario 2 elaborates on this case, as depicted in Fig. 2.4.

Investment in disaster risk mitigation constitutes one of the two additional feedback loops introduced in Scenario 2 (see Fig. 2.5). The loop R2 delineates how an intelligent contract investment in disaster risk reduction (DRR) measures can diminish asset damage, reduce risk premiums, and ultimately elevate insurance willingness, insured assets, and the budget of insurance companies. The reinforcing loop R2 is counterbalanced by loop B2, ensuring that the budget of insurance firms does not grow indefinitely.

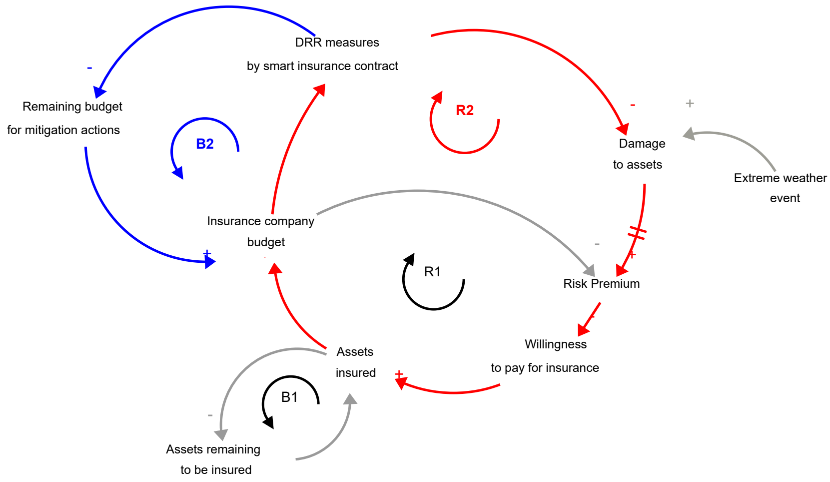

Fig. 2.5. CLD for investment in disaster risk reduction (Scenario 2) [38].

While this approach is geared towards diminishing disaster risk, there exists the possibility of a negative balance in an insurance company's budget. This can occur due to a reduction in risk premium payouts resulting from a decrease in disaster events, making it challenging to recover the initial investment in disaster risk reduction. Consequently, the introduction of a fixed premium price becomes necessary. The empirical model structure, known as a stock and flow model, simulating the system's behaviour, is established based on developed causal loop diagrams (CLDs) for case study Scenario 2. The results of the model simulation are presented and elucidated in Publication 1.

Scenario 3 model

In Scenario 3, referred to as the 'smart contract approach', a fixed premium concept is considered. Under this methodology, the disparity between insurance payouts and the established risk premium or a percentage of the insurance company's profits is utilized to reimburse the initial government bond investment in disaster risk reduction measures.

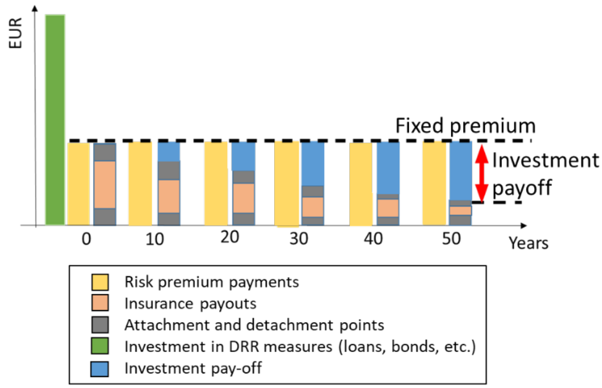

Fig. 2.6. Illustration of insurance companies' payment flows with smart contract approach (Scenario 3) [38].

To counteract the effects of loop R2 in the insurance system model provided, it becomes essential to introduce a fixed premium that is not contingent on asset damage. This fixed premium is determined based on historical data at the time of fixation. Consequently, the causal loop diagram (CLD) for the smart contract technique in Fig. 2.7 does not incorporate the connection between asset damage and risk premium. The proposed CLD underwent scrutiny and received approval for further utilization in a system dynamics (SD) stock and flow model by a panel of experts in SD and insurance.

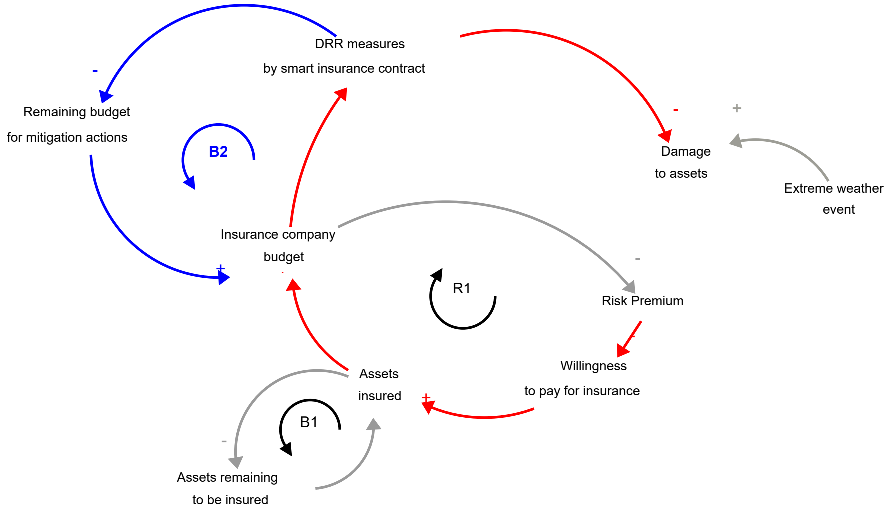

Fig. 2.7. CLD for smart contract approach (Scenario 3) [38].

The total expenditure of the company in Scenario 1 differs from the approaches in Scenarios 2 and 3, where insurance firms' expenditure encompasses both the pay-off of investments and payouts to insured assets after damage occurs. The costs incurred by insurance companies, estimated as the total in the SD model, can be utilized to compare the overall costs of transitioning from conventional insurance schemes to smart contracts in the business-as-usual (BAU) scenario. Evaluating the total disaster costs involves summing up the damage to all assets in the area and the expenditure on disaster risk reduction (DRR) measures to assess the overall efficacy of the analyzed scenarios.

The study indicates that implementing flood risk reduction measures may expose other assets in the vicinity to risk beyond the insured assets. Investing in DRR using this strategy can lead to reduced risk and risk premiums, thereby increasing people's willingness to pay for insurance. The system dynamics (SD) model allows the simulation of changes in the localized insured asset count. Only payments for risk premiums and payouts from investment gains are recorded as income and results, respectively. Profit for insurance firms is defined as the difference between income and results. The simulation results for Scenario 3 are presented and discussed in Publication 1.

Comparison of scenarios

In this section, a comparative analysis of the statistics obtained from 1000 simulation runs for each scenario is presented. These statistics shed light on the behavior of the following parameters: insured assets area, insurance company profit, insurance company expenditure, and total costs of disasters. The selected parameters for comparative analysis allow us to comprehend the differences in each insurance mechanism and their impact on insurance companies' business.

The statistics of the insured asset area are depicted in Table 2.1. In Scenario 1, the mean insured asset area for all simulation runs is approximately 2.48×10^5 m^2. The minimum insured asset area is 1.09×10^5 m^2, while the maximum is significantly larger, at 4.93×10^5 m^2. Scenario 2 presents a different picture, with the mean insured asset area notably higher, at 5.11×10^5 m^2. The standard deviation in Scenario 2, equal to 3.51×10^4 m^2, is much smaller than in Scenario 1, suggesting that simulation results for the insured asset area are more tightly clustered around the mean.

Table 2.1

Statistics of Insured Asset Area

Statistics	Scenario 1	Scenario 2	Scenario 3
Mean of insured assets area	$2.48{\times}10^5$	$5.11{\times}10^5$	N/A
Std. Dev. of insured assets area	$8.86{\times}10^4$	$3.51{\times}10^4$	N/A
Min of insured assets area	$1.09{\times}10^5$	$3.33{\times}10^5$	N/A
25 % percentile of insured assets area	$2.03{\times}10^5$	$4.76{\times}10^5$	N/A
75 % percentile of insured assets area	$3.05{\times}10^5$	$5.33{\times}10^5$	N/A
Max of insured assets area	$4.93{\times}10^5$	$5.33{\times}10^5$	N/A

*N/A – not applicable

In contrast to the other scenarios, Scenario 3 exhibits unique characteristics as the risk premium value is set constant; hence, the insured asset area in all simulations is equal to $4.63 \cdot 10^5$ m^2. Scenario 2 presents a higher average insured asset area, while Scenario 1 shows a lower average insured asset area than Scenario 3. This tendency is well presented by histograms in Fig. 2.8, where, for Scenario 1, the graph is skewed towards lower insured asset area values; for Scenario 2, the graph is skewed towards higher insured asset area values. And for Scenario 3, the insured asset area is the same for all simulation runs.

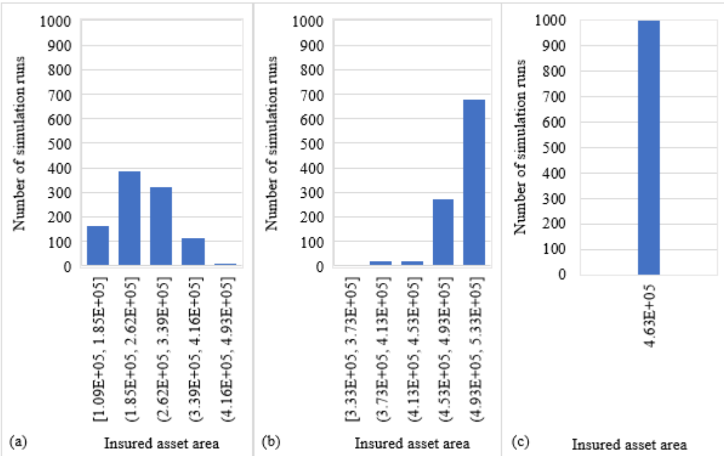

Fig. 2.8. Histograms for insured asset area in (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

The statistics for the profitability of insurance companies across three scenarios are shown in Table 2.2. In Scenario 1, the mean insurance company profit is EUR 34.6 million, with a standard deviation of EUR 13.5 million, indicating a considerable range in profit levels based on simulation-run hazard occurrences. The lowest profit value is EUR –34.9 million, suggesting the probability that the insurance business could suffer a loss. About EUR 42.4 million represents the 75th percentile, indicating that 25 % of simulation runs show profits higher than this value. The highest profit of all simulations is EUR 98.1 million.

Scenario 2 exhibits different statistical values. In comparison to Scenario 1, the average insurance company profit is noticeably larger, at about EUR 67 million, indicating a better degree of profitability. However, the standard deviation is EUR 30.8 million, showing that profit levels can vary significantly compared to Scenario 1. The minimal profit recorded is EUR –20.5 million, pointing to a reduced potential loss for the insurance firm. In 25 % of simulation runs, the company will produce earnings higher than the ones shown by the 75th percentile, about EUR 89.9 million. In all simulation runs, a maximum profit of EUR 146 million was recorded.

Table 2.2

Statistics of Insurance Company Profit

Statistics	**Scenario 1**	**Scenario 2**	**Scenario 3**
Mean	3.46×10^7	6.70×10^7	2.79×10^7
Std. Dev.	1.35×10^7	3.08×10^7	4.55×10^7
Min of insurance company profit	-3.49×10^7	-2.05×10^7	5.15×10^6
25 % percentile of insurance company profit	2.72×10^7	4.55×10^7	2.55×10^7
75 % percentile of insurance company profit	4.24×10^7	8.99×10^7	3.08×10^7
Max of insurance company profit	9.81×10^7	1.46×10^8	3.08×10^7

The mean average insurance company profit in Scenario 3 is EUR 27.9 million, which is less than in Scenario 2 but more than in Scenario 1. In comparison to the other scenarios, Scenario 3 standard deviation of EUR 4.55 million is relatively low, indicating less fluctuation in profit levels among simulation runs. The minimal profit that has been recorded is roughly EUR 5.15 million. The documented maximum profit is EUR 30.8 million, which also represents the 75th percentile. Corresponding to the statistics in Table 2.2 above, Fig. 2.9 shows the histograms for insurance company profit in three scenarios. The largest average profit is found in Scenario 2. Despite having a lower average profit, Scenario 3 has the lowest profit variability, suggesting a more stable and predictable scenario for the insurance company, while Scenario 1 shows lower average profitability and greater profit level variability.

The three separate scenarios from the perspective of companies' spending are represented in Table 2.3. In Scenario 1, the mean value of expenditure in the total number of simulation runs is EUR 1.36 million. In Scenario 2, it is EUR 26.2 million, and in Scenario 3, it is EUR 4.10 million. A higher standard deviation indicates greater variability in spending in Scenario 2, equal to EUR 12.3 million, while for Scenarios 1 and 3, it is EUR 1.41 million and EUR 4.55 million, respectively. The minimum expenditure is 0, while in Scenario 3, it is EUR 1.20 million.

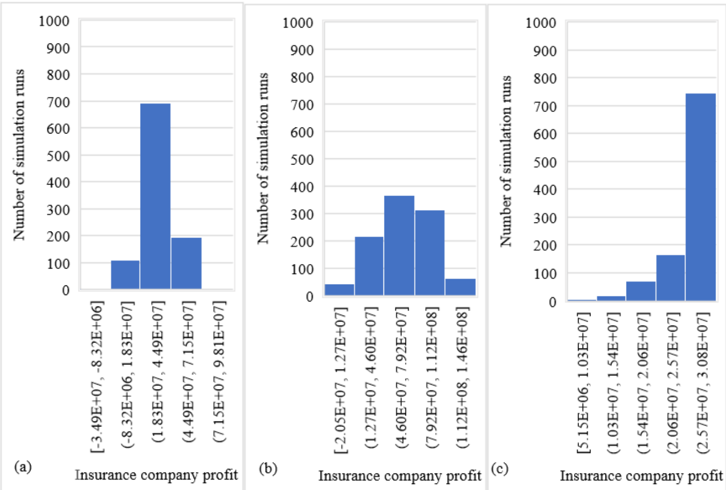

Fig. 2.9. Histograms for insurance company profit in (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

According to the statistics presented in Table 2.3 and the histograms in Fig. 2.10 for insurance company expenditure, there is significantly higher expenditure expected for the insurance company in Scenario 2 compared to Scenarios 1 and 3. Similarly, as for insurance company profit, Scenario 3 has a different distribution pattern for insurance company expenditure. In Scenario 3, the proportion of simulation runs with lower expenditure is much higher than for Scenarios 1 and 2, appearing as a skewed histogram graph towards lower values.

Table 2.3

Statistics of Insurance Company Expenditure

Statistics	Scenario 1	Scenario 2	Scenario 3
Mean of Total insurance company expenditure	1.36E + 06	2.62E + 07	4.10E + 06
Std. Dev. of total insurance company expenditure	1.41E + 06	1.23E + 07	4.55E + 06
Min of total insurance company expenditure	0.00E + 00	0.00E + 00	1.20E + 06
25% percentile of total insurance company expenditure	0.00E + 00	1.76E + 07	1.20E + 06
75% percentile of total insurance company expenditure	1.89E + 06	3.39E + 07	6.49E + 06
Max of total insurance company expenditure	7.12E + 06	6.83E + 07	2.69E + 07

Finally, the total costs of the disaster are compared among the analyzed scenarios in Table 2.4. Scenarios 2 and 3 show similar statistical outputs, as the applied disaster risk measures considered in these scenarios have the same effect on reducing disaster risk and, consequently, the damage costs. Scenarios 1 and 3 exhibit significantly lower mean and maximum values of total disaster costs compared to Scenario 1. This information is consistent with the histogram graphs shown in Fig. 2.11, where Scenarios 2 and 3 have similar skewed graphs towards lower values in the total cost of disaster.

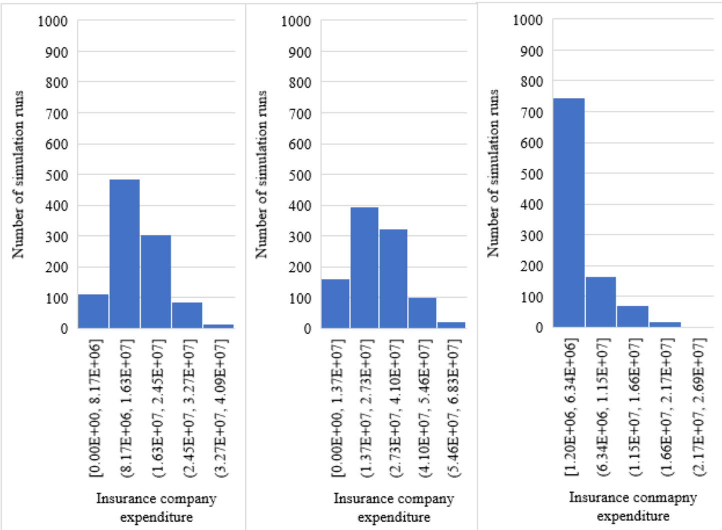

Fig.2.10. Histograms for insurance company expenditure in (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

Table 2.4

Statistics of the Total Costs of Disaster

	Scenario 1	Scenario 2	Scenario 3
Mean of total costs of disasters	6.99E + 07	7.90E + 06	7.34E + 06
Std. Dev. of total costs of disasters	3.02E + 07	1.12E + 07	1.05E + 07
Min of total costs of disasters	0.00E + 00	0.00E + 00	0.00E + 00
25 % percentile of total costs of disasters	4.92E + 07	0.00 E + 00	0.00E + 00
75 % percentile of total costs of disasters	8.99E + 07	1.79E + 07	1.36E + 07
Max of total costs of disasters	1.58E + 08	5.86E + 07	5.38E + 07

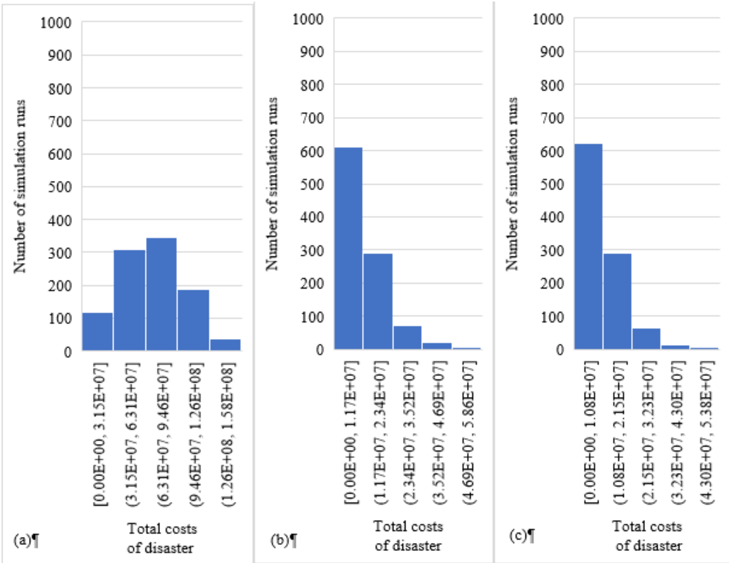

Fig. 2.11. Histograms for total costs of disaster in (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

Summarizing the comparison of the selected model parameters among the defined scenarios, the results indicate that Scenario 1 has a lower number of insured assets with higher total disaster costs compared to Scenarios 2 and 3. Therefore, Scenario 1 can be considered less desirable for local communities. Scenario 2 proved to be the most profitable among the analyzed scenarios; however, Scenario 3 exhibited more consistency in profitable outcomes. Moreover, Scenario 3 did not show any cases of negative values in profit, unlike the other two scenarios. Such differences between scenarios are also reflected in the statistics of the insurance company's expenditure.

CONCLUSIONS AND RECOMMENDATIONS

The Doctoral Thesis aimed to fill the knowledge gap on how new insurance instruments embedded in a proactive role of the insurance sector can be used for co-financing disaster resilience projects as mitigation and adaptation strategies enhancing community resilience against weather-related hazards.

The Doctoral Thesis wanted to demonstrate the effectiveness of integrating smart insurance contracts to be substantial to enhance the resilience of communities and reduce the socio-economic impact of natural disasters and socio-natural hazards, leading to more sustainable and adaptive disaster risk management strategies. A novel mechanism based on a Bayesian adaptive insurance scheme addressing flooding risk directed toward public administration has been proposed. This mechanism incorporates smart contracts and is further applied in developing a system dynamics-based urban assessment tool for socio-natural hazards, with a specific focus on floods in the Latvian context.

This doctoral research underscores the pivotal role played by insurance mechanisms in mitigating climate change-related disasters and safeguarding lives, livelihoods, and critical infrastructure. By deploying a comprehensive approach involving robust risk assessment, innovative insurance mechanisms, incentives for risk reduction, capacity building, stakeholder collaboration, and continuous monitoring and evaluation, the outputs of the Doctoral Thesis are relevant, enhancing community resilience and propelling sustainable development amid the complex challenges posed by climate change. Recognizing the evolving nature of climate risks, the Doctoral Thesis demonstrates how fostering innovation towards the effectiveness and accessibility of insurance mechanisms in the ever-changing landscape provides policy support toward DRR strategies and planning.

The Doctoral Thesis is a comprehensive study presenting fundamental insights and strategic recommendations for stakeholders, particularly public administrations, insurance companies, policymakers, and disaster risk managers. The author particularly favours the innovative Bayesian adaptive insurance mechanisms implementing smart contracts. This study highlights the usefulness of the system dynamics modelling approach for examining the feedback loops that govern the behaviour of complex systems related to the insurance mechanism of disaster insurance. The study aims to solve an existing problem in conventional disaster insurance mechanisms, which aims only to provide financial safety for asset recovery after a disaster event and not to decrease the risk of disaster itself. This problem is especially becoming topical with climate-related disaster risk increases and can lead only to higher damage costs in the long term.

The analysis of results unfolds key conclusions and offers a set of crucial recommendations, harmonizing diverse perspectives for effective risk reduction and resilience enhancement presented as follows.

Conclusions

- The study promotes a multidisciplinary approach combining legislative, engineering, and actuarial aspects to develop a comprehensive assessment tool for insurance against socio-natural hazards.
- The Thesis introduces a financial scheme for flood risk management, merging upfront investments with insurance mechanisms, in line with resilience bonds concept.
- The author emphasizes the role of engineering in risk assessment, cost-benefit analysis, and mitigation work design, guided by the European regulatory framework.
- The study suggests integrating blockchain technology for real-time climate data, damage recording, and smart contract implementation, adapting to climate trends.
- Blockchain technology is highlighted for its role in enabling real-time risk assessment and automatic contract updates, aiding precise insurance policy pricing.
- The Thesis encourages insurance companies to allocate surpluses towards disaster risk reduction (DRR) strategies, enhancing societal goals and disaster resilience.
- The author stresses the importance of research in smart contracting, blockchain, and Bayesian adaptive design for flood risk insurance, especially in urban areas.
- System dynamics modelling is identified as key in analysing complex systems' behaviour, addressing gaps in traditional disaster insurance focused on post-disaster recovery.
- The author proposes a new insurance model incorporating system dynamics, aiming to reduce disaster risk and not just provide post-disaster financial safeguards.
- The Thesis introduces a novel insurance mechanism, shifting from traditional models to more dynamic and effective approaches in disaster risk management.
- The new insurance model supports disaster risk mitigation investments, demonstrating benefits in reduced disaster costs and increased revenues for insurance companies.
- The proposed mechanism suggests a dynamic, smart contract approach, offering potential improvements in disaster resilience and community protection against weather hazards.
- The research recommends a premium risk calculation for developing quantitative infrastructure resilience models, aligning with regulations for resilience bonds.
- The author advocates for insurance companies to play a proactive role in societal well-being by investing in DRR initiatives, reflecting the evolving role of insurance in risk management.
- The author highlights the need for a holistic risk reduction approach in urban systems, involving policymakers, economists, urban planners, engineers, insurance companies, and scientists.
- The methodology aligns with sustainable development plans and is relevant for urban disasters, emphasizing collaboration among insurance companies, policymakers, and disaster risk managers for effective implementation.

Recommendations

- Future developments should include Monte Carlo simulations with real-world data to validate theoretical flood risk models.

- The approach, applicable to different risks, needs further development based on data quality in feasibility studies for resilient processes.
- Future work should foster dialogue between engineering and actuarial approaches, with legal perspectives clarifying smart contract effectiveness in multiperiodic scenarios.
- Insurance organizations should use diverse methods like break-even analysis for strategic planning, addressing information asymmetry and enhancing competitiveness.
- Cultural, behavioural, and educational factors are vital in understanding insurance demand, affecting willingness to pay beyond policy price and benefits.
- Continuous collaboration between legislative, engineering, and actuarial professionals is essential to refine the assessment tool for the insurance sector, quantifying the benefit of mitigative risk reduction measures.
- Research should integrate blockchain-based risk mitigation tools with existing frameworks like SECAPs for Municipalities, ensuring coordinated urban resilience.
- The methodology needs further real-world validation, possibly through pilot projects with insurance organizations to evaluate blockchain-based risk mitigation tools.
- Future research should validate the innovative insurance mechanism in different contexts and regions, refining the system dynamics model to aid decision-makers.

The Thesis lays the groundwork for transformative advancements in the realm of disaster risk management, emphasizing the critical role of innovative insurance mechanisms in building resilient communities within the continuously evolving challenges of climate change. The insights and methodologies presented herein contribute to a growing body of knowledge with practical implications for diverse stakeholders involved in the complex landscape of disaster resilience and sustainable development.

The integration of these conclusions and recommendations provides a roadmap for stakeholders, policymakers, and researchers to navigate the complexities of flood risk management, leveraging innovative technologies and collaborative approaches for a resilient and sustainable future.

REFERENCES

[1] Swiss Re-Sigma, "Natural catastrophes and man-made disasters in 2013: large losses from floods and hail; Haiyan hits the Philippines," *Swiss Re*, no. 1, p. 52, 2014, [Online]. Available: http://www.pacificdisaster.net/pdnadmin/data/original/SwisRe_2014_Natural_Catastrophes_sigma1_2014_en.pdf%0Afile:///K:/guilherme.mohor/OneDrive/Referencias/Referencias-artigoMario/2014 Swiss Re sigma1_2014_en.pdf.

[2] United Nations Office for Disaster Risk Reduction, *Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future*, no. April. 2022.

[3] S. Paleari, "Disaster risk insurance: A comparison of national schemes in the EU-28," *Int. J. Disaster Risk Reduct.*, vol. 35, no. October 2018, p. 101059, 2019, doi: 10.1016/j.ijdrr.2018.12.021.

[4] L. Bevere and F. Remondi, "Natural catastrophes in 2021: the floodgates are open," *Swiss Re Inst.*, no. 1, 2022.

[5] C. Quinto, *Insurance Systems in Times of Climate Change, Schulthess Juristische Medien AG, Zurich*. Basel – Geneva, 2011.

[6] A. Galderisi and G. Limongi, "A comprehensive assessment of exposure and vulnerabilities in multi-hazard urban environments: A key tool for risk-informed planning strategies," *Sustain.*, vol. 13, no. 16, 2021, doi: 10.3390/su13169055.

[7] S. R. Chikabvumbwa, N. Salehnia, R. Manzanas, C. Abdelbaki, and A. Zerga, "Assessing the effect of spatial–temporal droughts on dominant crop yield changes in Central Malawi," *Environ. Monit. Assess.*, vol. 194, no. 2, pp. 1–16, 2022, doi: 10.1007/s10661-021-09709-4.

[8] M. Mededjel, G. Belalem, F. Z. N. Benadda, and S. Kadakelloucha, "A Blockchain Application Prototype for the Internet of Things," *J. Commun. Softw. Syst.*, vol. 18, no. 2, pp. 124–136, 2022, doi: 10.24138/JCOMSS-2021-0129.

[9] D. P. Alyakina and G. F. Khisamova, "Methodology for Rating of Insurance Portfolio," *Mediterr. J. Soc. Sci.*, no. November 2014, 2014, doi: 10.5901/mjss.2014.v5n24p137.

[10] A. Thomas and R. Leichenko, "Adaptation through insurance: Lessons from the NFIP," *Int. J. Clim. Chang. Strateg. Manag.*, vol. 3, no. 3, pp. 250–263, 2011, doi: 10.1108/17568691111153401.

[11] A. J. Pagano, F. Romagnoli, and E. Vannucci, "Non-Incomes Risk Mitigation Mechanisms for Cultural Heritage: Role of Insurances Facing Covid-19 in the Italian Context," *Environ. Clim. Technol.*, vol. 26, no. 1, pp. 871–882, 2022.

[12] A. J. Pagano, F. Romagnoli, and E. Vannucci, "Quantitative and Financial Aspects of Resilience Bonds in the Context of Recursive Insurance Contracts. A Cost Benefit Analysis," *Environ. Clim. Technol.*, vol. 24, no. 3, pp. 387–402, 2020, doi: 10.2478/rtuect-2020-0111.

[13] A. J. Pagano, F. Romagnoli, and E. Vannucci, "Insurance against Natural Hazards: Critical Elements on the Risk Premium Evaluation in the Italian Context," *Environ. Clim. Technol.*, vol. 24, no. 3, pp. 373–386, 2020, doi: 10.2478/rtuect-2020-0110.

[14] A. J. Pagano, F. Romagnoli, and E. Vannucci, "Implementation of Blockchain Technology in Insurance Contracts against Natural Hazards: A Methodological Multi-Disciplinary Approach," *Environ. Clim. Technol.*, vol. 23, no. 3, 2019, doi: 10.2478/rtuect-2019-0091.

[15] W. J. W. Botzen, J. Bergh, and J. M. Van Den Bergh, "Monetary valuation of insurance against climate change risk," *Work. Manuscr.* , vol. 53, no. May, pp. 1–6, 2012, doi: 10.1111/j.1468-2354.2012.00709.x.

[16] D. Petersen, "Automating governance: Blockchain delivered governance for business networks," *Ind. Mark. Manag.*, vol. 102, no. November 2021, pp. 177–189, 2022, doi: 10.1016/j.indmarman.2022.01.017.

[17] X. Wang, W. Yang, S. Noor, C. Chen, M. Guo, and K. H. Van Dam, "Blockchain-based smart contract for energy demand management," *Energy Procedia*, vol. 158, pp. 2719–2724, 2019, doi: 10.1016/j.egypro.2019.02.028.

[18] G. De Gregorio, *Il contratto di assicurazione*. Giuffrè, 1987.

[19] S. Landini, "Reticenze dell'assicurato e annullabilità del contratto," *Resp. civ. e prev*, 2011.

[20] A. J. Pagano, F. Romagnoli, and E. Vannucci, "Implementation of blockchain technology in

insurance contracts against natural hazards : a methodological multi-disciplinary approach," *Environ. Clim. Technol.*, vol. 23, no. 3, pp. 211–229, 2019, doi: 10.2478/rtuect-2019-0091.
[21] H. C. Kunreuther and E. O. Michel-Kerjan, "The Development of New Catastrophe Risk Markets," *Annu. Rev. Resour. Econ.*, vol. 1, no. 1, pp. 119–137, 2009, doi: 10.1146/annurev.resource.050708.144302.
[22] Actuaries Institute, "The Impact of Big Data on the Future of Insurance," 2016.
[23] A. Bellieri dei Belliera, M. Galeotti, A. J. Pagano, G. Rabitti, F. Romagnoli, and E. Vannucci, "Flood risk insurance: the Blockchain approach to a Bayesian adaptive design of the contract ," in *Afir. ERM*, 2019, no. May, pp. 1–19.
[24] N. Kapucu, Y. 'Gurt' Ge, Y. Martín, and Z. Williamson, "Urban resilience for building a sustainable and safe environment," *Urban Gov.*, vol. 1, no. 1, pp. 10–16, 2021, doi: 10.1016/j.ugj.2021.09.001.
[25] Y. Paudel, W. J. W. Botzen, and J. C. J. H. Aerts, "Estimation of insurance premiums for coverage against natural disaster risk: An application of Bayesian Inference," *Nat. Hazards Earth Syst. Sci.*, vol. 13, no. 3, pp. 737–754, 2013, doi: 10.5194/nhess-13-737-2013.
[26] D. Serre and C.Heinzlef, "Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks. International Journal of Disaster Risk Reduction," *Int. J. Disaster Risk Reduct.*, 2018.
[27] R. Feng, "Traditional Insurance," 2023, pp. 85–117.
[28] D. Bruneau, "A framework to quantitatively assess and enhance the seismic resilience of communities," *EERI Spectra*, pp. 733–752, 2003.
[29] N. R. Dalezios, "Environmental Hazards Methodologies for Risk Assessment and Management," *Water Intell. Online*, vol. 16, no. January 2017, p. 9781780407135, 2017, doi: 10.2166/9781780407135.
[30] A. Blumberga *et al.*, *System Dynamics for Environmental Engineering Students*, 1st editio. Riga: RTU Izdevniecība, 2011.
[31] J. D. Sterman, "Learning in and about complex systems," *Syst. Dyn. Rev.*, vol. 10, no. 2–3, pp. 291–330, 1994, doi: 10.1002/sdr.4260100214.
[32] D. Kurnianingtyas, B. Santosa, and N. Siswanto, "A System Dynamics for Financial Strategy Model Assessment in National Health Insurance System," in *Proceedings of the 2020 2nd International Conference on Management Science and Industrial Engineering*, 2020, pp. 44–48, doi: 10.1145/3396743.3396754.
[33] G. A. M. LATVIAN CENTER FOR ENVIRONMENT, "Preliminary flood risk assessment for 2019–2024," 2019.
[34] M. Feofilovs and F. Romagnoli, "Dynamic assessment of urban resilience to natural hazards," *Int. J. Disaster Risk Reduct.*, vol. 62, p. 102328, 2021, doi: https://doi.org/10.1016/j.ijdrr.2021.102328.
[35] B. G. Reguero *et al.*, "Financing coastal resilience by combining nature-based risk reduction with insurance," *Ecol. Econ.*, vol. 169, p. 106487, 2020, doi: https://doi.org/10.1016/j.ecolecon.2019.106487.
[36] S. Surminski, L. M. Bouwer, and J. Linnerooth-Bayer, "How insurance can support climate resilience," *Nature Climate Change*, vol. 6, no. 4. 2016, doi: 10.1038/nclimate2979.
[37] S. Cosma, S. Principale, and A. Venturelli, "Sustainable governance and climate-change disclosure in European banking: the role of the corporate social responsibility committee," *Corp. Gov. Int. J. Bus. Soc.*, no. September 2021, 2022, doi: 10.1108/cg-09-2021-0331.
[38] M. Feofilovs, A. J. Pagano, M. Spiotta, E. Vannucci, and F. Romagnoli, "Climate change-related disaster risk mitigation through innovative insurance mechanism : a System Dynamics model application for a case study in Latvia Climate change-related disaster risk mitigation through Innovative Insurance Mechanism: A System Dynamics Model Application for a Case Study in Latvia," *Risks.,* Vol. 12, no. 43, pp. 1–23.

Andrea Jonathan Pagano received a master's in Law from the University of Pisa, Italy, in 2016. After graduating, he became a tutor at the same university, supporting master's students in developing their theses on his expertise. In 2018, A. J. Pagano started his doctoral studies at the Riga Technical University Institute of Energy Systems and Environment. His research framework creates a link between his background in law, engineering aspects, and environmental insights. With this background, he was a lecturer at the Riga Technical University Institute of Energy Systems and Environment in the '*Risk and Resilience*' course.
In 2020 and 2021, A. J. Pagano was a visiting Fellow in the Department of Economics and Management at the University of Pisa. Since 2021, he has been lecturing on '*Insurance Risk: Evaluation and Management*' in the Risk Management program at the University of Pisa.
A. J. Pagano is also a prolific author, with an extensive number of Italian and International publications, marking him as a significant contributor to the scientific discourse towards various academic fields.