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Resilience Bonds and the Financing of Resilient Infrastructure

By

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Declaration

I, Yang Song, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

“We are not defined by who we are but who we try to be”

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Abstract

Within the past 50 years, the number of catastrophic events has increased significantly. The need for resilience is fast gaining attention globally in the mitigation of risks for potential infrastructure failures and in the goal to reduce unexpected economic losses. However, as a fundamental global issue, the lack of public funding for investment in infrastructure projects has meant increased expectations for private finance involvement. As a newly emerged financial tool, resilience bonds offer a novel way to support unlocking finance, especially for investment in resilient infrastructure projects. The research conducted in this thesis offers several insights on the innovative resilience bonds and seeks to answer the following question: what are the impacts of resilience bonds in the development of resilient infrastructure? The thesis also investigates the following sub-questions: how to price resilience bonds in the emerging market based on different resilient infrastructure projects; identify the factors that influence the prices of the resilience bond; and analyse how the concept of resilience bond can be extended to global issues. The thesis begins by introducing the research background followed by a comprehensive and critical review of the existing literature on securities in the field related to infrastructure investment. Then, new methodological contributions on the valuation model of resilience bonds with different catastrophe scenarios are presented in case study chapters. Lastly, the thesis extends the concept of resilience bond in the consideration of global pandemic catastrophes and multi-hazard urban disaster risk in Istanbul. The derived results highlight the benefits of applying resilience bonds in the development of resilient infrastructure projects. In addition, the obtained findings show the performance and price of the resilience bond based on the different project mechanisms and valuation models. We anticipate that the findings from this study will lead to the expansion of resilience bonds in the financial market to help public authorities worldwide shift the finance fulcrum away from sole reliance on traditional public investment.

Impact Statement

Sustainable development of infrastructure systems is receiving attention from governments around the world. Improving the resilience of infrastructure in advance is deemed as optimal preparedness for cities choosing to abide by a framework of sustainable development. However, there is a gap between the limited public resources available and the infrastructure investment needed for public sectors worldwide. This study reviews the financial tools that can be applied to support resilient infrastructure development and presents the newly published resilience bond with the engagement of resilient infrastructure development. The resilience bond will efficiently and effectively bridge the gap in the investment of resilient infrastructure projects, and in so doing release the heavy financial burden on governments in different countries. Furthermore, the issuance of resilience bonds can expand the potential investor's range into institutional, public and private investors in the financial market who are interested in infrastructure development and desire to help societies avoid unexpected losses from future catastrophes.

From the theoretical perspective, this research fills the gap in the existing insurance-linked securities literature, especially the literature for resilience bonds. The thesis reviews and compares the most commonly used financial tools involved in the development of resilience for infrastructure, including fund raising; it demonstrates the advantages and disadvantages of each financial tool in the context of investment. The review offers the foundation for future academic references in the field of valuation of insurance-linked securities since there is scant literature dedicated to the newly published resilience bond.

From the application perspective, this thesis uses a combination of modeling techniques, numerical simulations, scenario analysis, and case studies to investigate the newly published resilience bond. The findings from the tests of resilience bond pricing model under different catastrophe scenarios offers guide prices of the bonds to be issued in the financial market.

From the concept extension perspective, this thesis discusses the effectiveness of applying resilience bonds in global issues, such as Covid-19 and multi-hazard disaster risk in Istanbul, Turkey. The results show the performance evaluation of the mechanism for resilience bond and analyse the influence of resilience bond in the development of the resilient projects.

Contents

List of figures

List of tables

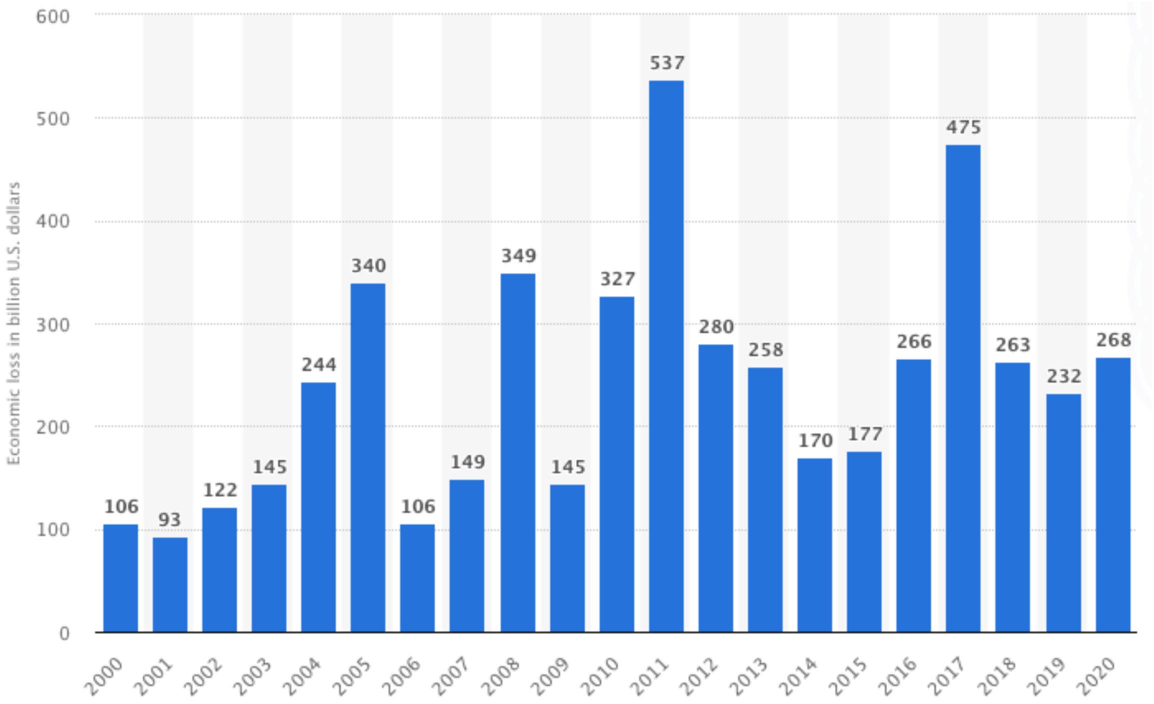
List of Abbreviations

CAT	Catastrophe
CSR	Corporate Social Responsibility
CIR	Cox-Ingersoll-Ross
ESG	Environment, Social and Governance
EBRD	European Bank for Reconstruction and Development
FEMA	Federal Emergency Management Agency
FINMA	Financial Market Supervisory Authority
FRM	Flood Risk Management
FRB	Forest Resilience bond
GIS	Geographical Information Systems
HILP	High Impact Low Probability
HPP	Homogeneous Poisson process
ILS	Insurance-Linked Securities
ITP	Intermodal Transportation Port
IBRD	International Bank for Reconstruction and Development
IDA	International Development Association
IMM	Istanbul Metropolitan Municipality
LIBOR	London Interbank Offered Rate
LCR	Low Carbon and Climate-Resilient
MTA	Metropolitan Transport Authority
NFIP	National Flood Insurance Program
PEF	Pandemic Emergency Financing Facility
PBI	Project Bond Initiative
PCS	Property Claim Services
PPP	Public and Private Partnership
SPV	Special Purpose Vehicle
SST	Swiss Solvency Test
T-Bill	Treasury Bonds
TCIP	Turkish Catastrophe Insurance Pool
YTM	Yield to Maturity

Chapter 1 Introduction

Catastrophe is understood to be an event that exceeds the capability of humans and causes widespread damage or suffering. Catastrophic events occur suddenly and cause multiple billions of losses each year across the world. It is noteworthy that the number of catastrophes has increased three times in the last 30 years. According to Posner (2004), catastrophe is defined as: "*the momentous tragic, usually sudden event marked by effects ranging from extreme misfortune to utter overthrow or ruin.*" Catastrophic events, whether natural or man-made, can impact human's daily life and destroy assets, since these disasters are real and growing. Natural catastrophes occur as a result of different natural processes on Earth, and occur as earthquakes, floods, hurricanes, and tsunamis. As Fig. 1-1 shows, natural catastrophes in 2020 resulted in around $268 billion in damages; and the highest record from the previous two decades occurred in 2011, where the number of natural catastrophes had increased sharply, leading to $537 billion in economic losses.

Figure 1-1 Economic losses from natural disaster events globally (2000-2020).



Source: (Statista 2021b).

The devastating Kobe earthquake in 1995 caused the disconnection of electric power and telecommunication infrastructure for one week, and racked up approximately $100 billion in losses (Chang and Nojima 2001). In recent years, the repercussions of natural catastrophes continue to threaten infrastructure and often cause significant infrastructure failures.

Infrastructure as a complex system comprises networks, sites, facilities, systems, and businesses that deliver goods and services for daily life and supports the development of economics, the environment and social well-being. Infrastructure allows people to function comfortably in daily life and boosts the economy significantly, since infrastructure stimulates both productivity and economic growth for countries globally. According to Fourie (2006), economists and urban planners have divided infrastructure into social (soft) infrastructure and economic (hard) infrastructure. *Social* infrastructure covers a range of services and facilities that promote social activity such as schools, universities, and hospitals, which brings externalities to the society where social marginal productivity is greater than private marginal productivity. Whereas *economic* infrastructure is the combination of basic facilities that promote economic activity; these include roads, electricity, telecommunications, water supply, and sanitation. Familoni (2006) states that both social and economic infrastructure are essential factors for facilitating and accelerating socio-economic development; the development of social and economic infrastructure will ensure the exchange of scarce commodities to lower prices and costs. However, early research from Hall and Jones (1999) advocates that the development of social infrastructure is the foundation for promoting better use of economic infrastructure since higher economic growth will improve the quality of life for the society. Thus, as the backbone of our societies, the question, how to reduce the risk of infrastructure failure is gaining attention because in the meantime, changing climatic patterns are fostering increasing occurrences of natural catastrophes. In response, financial reimbursement from insurance services is considered as one of the most widely applied approaches in support of post-catastrophe recovery.

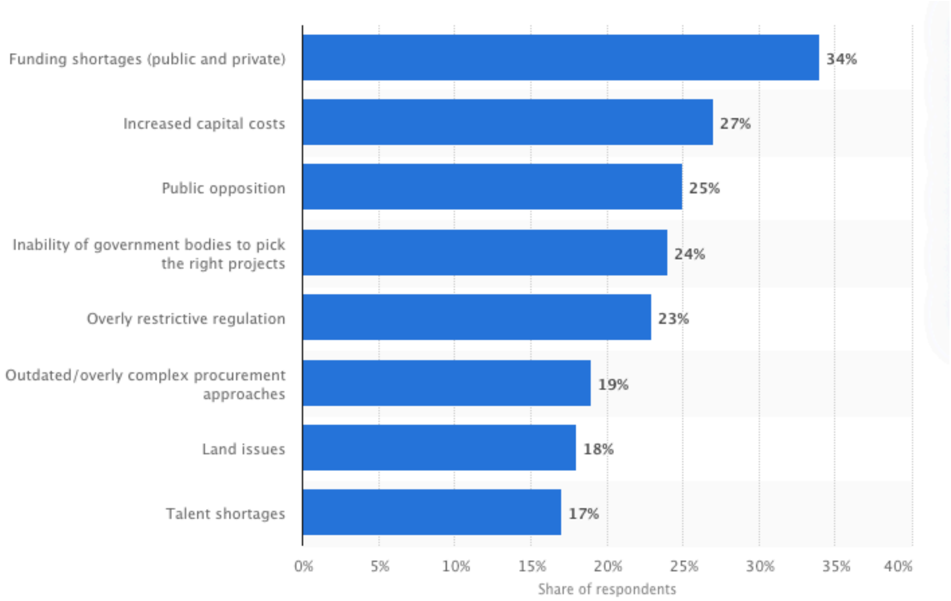
However, infrastructure which lacks insurance and is thus vulnerable to unexpected catastrophes, is likely to challenge governments everywhere. According to Munich-RE (2017), despite that the number of uninsured assets has decreased in recent years in industrialised countries, insurance gaps still exist in most developing and emerging countries. As the data shows from Statista (2021c), the global insured losses caused by natural disaster in 2020 was $75.82 billion, which is lower than the overall $268 billion global economic loss caused by natural disasters in 2020. Based on the losses shown in Fig, 1-1, only a small proportion of assets around the world are covered by insurance. Insurance is an efficient tool for guaranteeing financial security for the government from infrastructure failure, since the failure of the system may bring unmeasurable losses to societies. Insurance companies may be able to help governments with incentives to reduce losses from natural catastrophes, and also be in the position to analyse risks and exposures for individuals, corporations and governments (Picard 2008). In 1992, insurance-linked securities (ILS) emerged in the capital market after Hurricane Andrew due to the limited capacity of traditional (re)insurance companies and recession of the market. Two years later in 1994, the first ILS product, catastrophe (CAT) bond, appeared in the market and by 1997 was used widely (Bouriaux and MacMinn 2009). As the most typical ILS product, CAT bonds have played an essential role for the risks exchange between insurers and capital market investors; it combines financial instruments with insurance via intermediary (re)insurance companies through a risk diversification mechanism (J. D. Cummins and Weiss 2009; J. D. Cummins and Trainar 2009). However, and significant for our purpose in the present thesis, the design of catastrophe bonds may only respond to the post-catastrophe financial repayment, *not* to support the development of resilience of the infrastructure system *in advance*. Comprehensive insurance-linked securities are nevertheless expected to be created in the market, which can both insure the aftermath of financial losses and support the development of infrastructure. According to a document of HMGovernment (2011), infrastructure is the interconnected network of high-value assets, but the vulnerabilities of infrastructure are increasing; therefore, the vision of the government is to build resilience into infrastructure networks to ameliorate against catastrophes and prepare for the future changing climate.

At present, concern is widespread about whether existing and projected infrastructure facilities are resilient to the rising number of unpredictable catastrophes. To increase the resilience of the infrastructure and reduce the recovery time, the most efficient approach is a dynamic planning process capable of adapting to changing external contexts (Demuzere et al. 2014). An entity should avoid post-perception to the upgrading/adapting of the infrastructure assets after catastrophes or rely solely on the post-catastrophe reimbursement in order to recover the performance because it will impede the resilience development to the entity in advance. Building resilience into infrastructure is essential for mitigating vulnerability to natural catastrophes; therefore, infrastructure owners and operators, regulators and public authorities, emergency responders, and industry groups should cooperate to enhance the resilience of infrastructure systems (Cabinet-Office 2011). KPMG (2018) states that stable infrastructure is important to provide adequate support to the systems for individuals, businesses, nations, and societies. Ensuring the resilience of infrastructure will enhance the system to mitigate direct and indirect losses from unexpected catastrophes. As HMGovernment (2011) advocates, the country should be prepared to deal with the changes in climate and abide by the framework of the Climate Change Act (2008). Two aspects have been defined and applied to resilience by A. Rose (2004), of which the ‘inherent’ is the ability of the system to substitute other inputs when exposed to external shocks; and ‘adaptive’ is the ability to increase the input substitution possibilities from extra effort. Along with this consideration, the defining characteristics of the resilient infrastructure should be planned, designed, built, and operated to meet the requirements to prepare for and adapt to catastrophes and changing climate (Vallejo and Mullan 2017).

Despite the essential importance of infrastructure in countries, the extent of the capital spending which can be distributed to infrastructure sectors is contingent upon a country’s economic affluence and available resources. As per the OECD (2015c), governments are the traditional investors in infrastructure because most infrastructures are considered as public goods and generate positive externalities. However, infrastructure investment spending with public funds has increasingly led to public deficits and high public debt to GDP ratios; and this factor is the main reason for the decreased allocation of public funds to infrastructure. There is a clear divide between government funding and infrastructure investment, so governments worldwide are expected to devise ways to attract more private investors into sustainability investment for infrastructure (Panayiotou and Medda 2014). Infrastructure financing is a difficult issue for all governments, not to mention investment in resilient infrastructure that is facing unpredictable catastrophes. To begin to resolve the financing problem, different methods, tools and vehicles are being developed and have been applied to broaden the financing options for infrastructure projects, especially resilient infrastructure projects (Re:Focus 2015).

As we can observe in Fig. 1-2, funding shortages occupy a significant portion of the failure of infrastructure projects. Along with the growing global need for resilient infrastructure projects, strong demand for infrastructure investment funding has led to many creative financial tools in the financial market. One such innovative insurance-linked securities product – the resilience bond – emerged in the market in 2015. According to founders Vaijhala and Rhodes (2018), resilience bonds seek to raise up-front investment funds specifically for resilient infrastructure projects, that is, to improve the ability of infrastructure to persist and adapt to sudden catastrophes, while mitigating catastrophe risks and losses by unlocking broader development benefits. In effect, resilience bonds bring opportunities to expand the potential capital market investment by widening the diversity of investors from both public and private sector, as well as enhance potential cooperation between different infrastructure sectors. Ultimately, resilience bonds could become an efficient tool for financing resilient infrastructure development, raising lower-cost loans for individuals, corporations, municipalities and governments, and benefiting countries or regions where insurance gaps might exist.

Figure 1-2 Major reasons for infrastructure projects failure



Source: (Statista 2021a).

1.1 Research aims and structure of the thesis

This thesis conducts an analysis of resilience bonds to understand how the mechanism of the bond can be applied in the capital market and evaluates the effects of using the resilience bond in the development of resilient infrastructure under different scenarios. As a newly published bond, the resilience bond is seldom discussed in the literature and rarely applied to practical resilient infrastructure projects. This thesis also aims to contribute to the design of instructions for the resilience bond as well as discuss its application in the hedge of different catastrophes such as earthquakes, floods, and supply chain disruptions. The research from this thesis mainly seeks to answer the question:

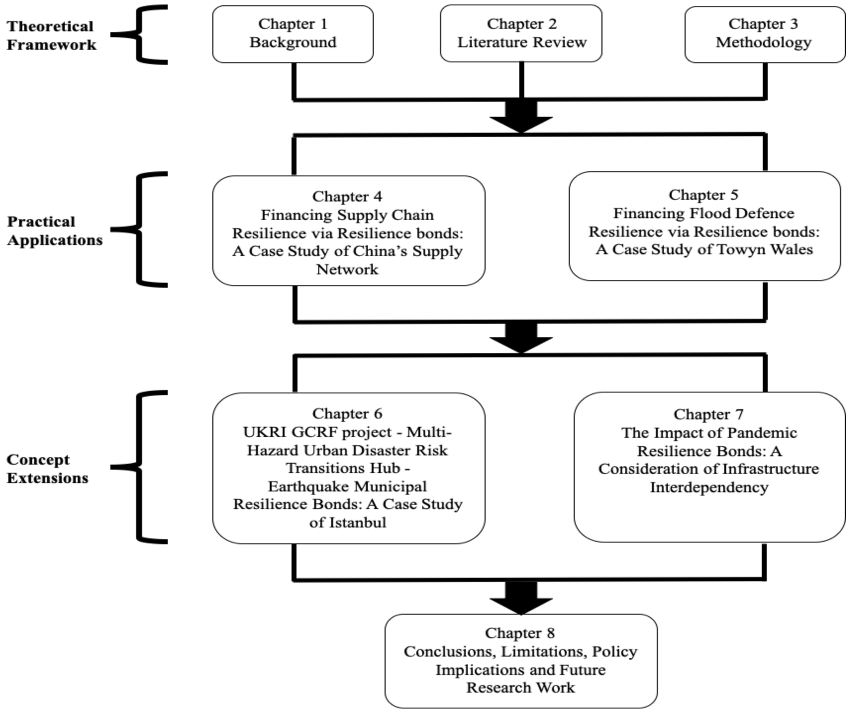
- What are the impacts of resilience bonds in the development of resilient infrastructure?

Thereafter, the thesis further investigates the following sub-questions:

- How resilience bonds can be priced in the emerging market based on different resilient infrastructure projects;
- What factors influence the prices of the resilience bond; and
- How the concept of resilience bond can be extended to global issues.

Figure 1-3 provides the structure of the resilience bond study in three main parts.

Figure 1-3 Structure of the thesis



The thesis is set out such that Chapter 1 provides the background of the research and identifies the issues existing in the infrastructure development for countries worldwide. As the backbone of an economy, the infrastructure system allows societies to function in a stable way. However, the increasing in the occurrence and consequences of catastrophes, thereby inflicting unmeasurable economic losses to cities, regions, and communities. In response, a growing number of entities understand that the improvement of resilience in infrastructure is likely to mitigate potential risks and reduce losses caused by catastrophic events. Therefore, this thesis has conducted research on an innovative financial tool especially designed to support resilient infrastructure development.

Chapter 2 reviews the literature of the most commonly used financial tools involved in the development of, as well as fund raising for, infrastructure in the capital market. The chapter also compares the advantages and disadvantages of each financial tool in the context of investment in resilient infrastructure development. The contribution of the theoretical part provides the foundation for the resilience bond, introduces it, and describes the basic functions of the resilience bond compared to other bonds in the financial market.

Chapter 3 studies the widely-used valuation models for securities, and reviews the catastrophe bond pricing model in order to develop the pricing model for resilience bonds. From the review of methodologies, we find that the resilience bond requires extra parameters in the definition of the impacts of the resilient infrastructure project on the whole system so that the price will be modeled based on the adaption of the catastrophe bond pricing model. As A. Rose (2004) remarks, "*Prices act as the 'invisible hand' that can guide resources to their best allocation, even in the aftermath of a disaster*"; Rose clearly expresses that pricing models are important for customers to estimate value and make decisions for investment (2004). Thereafter, a pricing model is built for each case study to provide the guidance price for the resilience bond to be published in the market.

Chapter 4 examines the resilience bond in the application of resilient supply chain development in China. Here we study the resilience of the supply chain by upgrading an existing connection hub to be a modern intermodal transportation port (ITP); the connection hub has been identified as a flexible node for improving resilience across the whole network. Issuing a resilience bond is expected to raise an up-front investment fund for the upgrading project, attract more potential investors, and offer insurance protection for the supply chain project to hedge the unpredictable catastrophes. The research conducted here has allowed us to develop the mechanism of the supply chain resilience bond for China, and build a pricing model using data from Willis Tower Watson (Shanghai) to provide fair guidance for the price of the bond in the Chinese market.

Chapter 5 elaborates a case study of the resilience bond applied for flood defense resilience for Towyn, Wales. We analyse the demand for resilience in the flood defense of Towyn and identify the challenges of the resilient enhancing project. In doing so, the study has developed the mechanism of using resilience bonds to finance the improvement of resilient flood defense projects for Towyn to avoid potential flooding risks in the future. In the research, we simulate the potential flood economic losses by testing three-level surges; we then price the bond by evaluating different probabilities combined with different surges. We also conduct a sensitivity analysis to study the influence of the price from different parameters. Finally, we formulate the mechanism of flood resilience bond with a guidance pricing model to help with the publishing of the bond in the UK market.

Chapter 6 involves a UKRI GCRF project for the Turkish government in the Multi-Hazard Urban Disaster Risk Transitions Hub that focuses on the earthquake resilient project in Istanbul. In the research, we review earthquake conditions in Istanbul and the demand for resilience in the future. To fulfill the development requirements from the government, we propose a conceptual model for applying a resilience bond to support the financing of resilient infrastructure development. Lastly, we discuss the possibility of the issuance of a resilience bond by the Istanbul Municipality that can be sold in the municipal bond market with the goal to widen the range of investors.

Chapter 7 is dedicated to an impact analysis of pandemic resilience bonds in the development of infrastructure interdependency. In addition, the chapter analyses the effects of resilience bonds in consideration of the current global pandemic context. A main contribution of this chapter is the investigation into the potential involvement of different infrastructure sectors as investors in resilient social infrastructure with the aim of reducing potential risks due to sudden pandemics in future.

Chapter 8 summarises the findings and results of the thesis, outlines the central conclusions and limitations of the research, and gives policy suggestions for future research.

Chapter 2 Literature Review

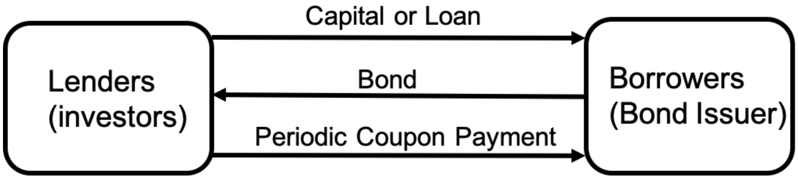
Nowadays, strong economic and high-density populated areas are exposed to a high risk of catastrophes. In most events, natural catastrophes have caused a huge amount of financial loss and death. Fortunately, insurance services offer protections when catastrophic losses meet the catastrophe trigger conditions. For example, non-life insurance can support the business to keep carrying on when any parts of components go out of service due to disasters. However, insurance companies would at some point in future face mega-catastrophes, bringing excess coverage and leading to bankruptcy. A mega catastrophe is an unexpected catastrophe with high impact and high magnitude; it has a low probability of occurrence but influences several entities directly or indirectly. Consequently, insurance-linked securities (ILS) such as catastrophe (CAT) bonds and resilience bonds have appeared in the market as popular alternative tools for saving recovery time and raising funds for financial reimbursement from catastrophic events. The CAT bond is widely adopted to transfer catastrophe risks to the capital market in order to hedge against unforeseen economic loss. However, an increasing number of communities are starting to consider preparing the system in advance rather than receiving reimbursement in the aftermath; doing so may efficiently provide protection in advance and reduce losses (Re:Focus 2015). In this circumstance the CAT bond shows less advantage because it only provides post-catastrophe reimbursement. Whereas the resilience bond now in the market fulfills the needs of those communities and can generate upfront funds for resilient infrastructure projects to prepare the system and provide insurance services at the same time.

Since financing resilient infrastructure projects is a global issue, and most governments around the world are facing financial stress in the development of infrastructure, different financial tools have been applied to release the financial burden on the public sector. Fixed-income securities are one of the most popular financial tools to help governments raise funds for infrastructure investment. In the following sections we will review the fixed-income securities and insurance-linked securities which are integral to resilient infrastructure development.

2.1 Bond structure and mechanism

An investment in new assets typically requires large funds. Therefore, private companies or public institutions may need to borrow additional funds instead of selling shares of stocks. Banks generally offer short-term loans, but long-term loans may require the issuance of bonds from issuers such as companies and municipalities (Richard A. Brealey et al. 2014). Bonds have been defined as asset classes along with stocks and cash equivalents. As a fixed-income tool, a bond is simply a loan from a lender to a borrower, such as a company. Instead of borrowing from a bank, a company receives money from investors who buy its bonds. In exchange for the capital, a company pays an interest coupon, e.g., the annual interest rate paid on a bond expressed as a percentage of the face value. As shown in figure 3-1, investors receive coupon payments based on the size of the principal and a pre-defined period. The interest rate for coupon payments could be variable or fixed. Bond issuers are obliged to pay interest or coupons to investors quarterly, semi-annually or annually and return the principal on the date of bond maturity.

Figure 2-1 How bonds work



Source: (Wallstreetmojo and Vaidya 2022)

Bonds are commonly used among entities, such as private corporations, municipalities and governments. The issuance of bonds, as loans between lenders and borrowers, involves several parties and the mechanism of a bond can be described thusly:

- Lender: the lender is the buyer of bonds in the capital market who wants to invest money now in exchange for future repayments, e.g., private or institutional investors.
- Borrower: the borrower is the seller of bonds in the capital market who raises money to finance operations and projects, e.g., governments, municipalities and companies.
- Coupon payment: the coupon payment is the interest received by investors who hold the bonds until maturity.

- Capital or Loan: capital or loan usually refers to the principal invested from the lenders to the borrowers.
- Maturity: maturity is the date when the principal of the bond is scheduled to be paid back from the issuer to investors. The length of the maturity period can be short-term or long-term. For instance, the maturity of the catastrophe bond is typically three to five years.
- Coupon rate and Coupon: the coupon rate is the rate of interest paid to the investor by the issuer annually, which will be influenced by the government-set interest rate. The bond coupon is the interest payment entitled by bond investors based on the pre-defined interest rate, which equals the face value x coupon rate.
- Yield rate: the yield rate is the rate of return generated from the investment. Yield to maturity will equal the coupon rate if the price of a bond is the same as its face value for investors. Otherwise, the yield to maturity is higher than the coupon rate if the price of a bond is at a discount of face value.
- High-yield bond: a type of junk bond that pays a high-interest rate with a lower credit rating.

Whereas, bond valuation is a method for theoretically determining a specific bond's market price; it includes computing the current value of the coupon payments in the future known as the present value of future cash flow and the principal value in the future maturity period, which is the present worth of the bond face value based on the up-to-date market interest rate. According to Richard A Brealey et al. (2012), the initial price of a bond is generally set at a face value of 100 or 1000, and the actual price of the bond is calculated as a percentage of the face value.

- Face value: the face value is used to define the nominal value of a bond. It is the final payment received by the bondholder at the end of maturity. The principal of a bond is recognised as the face value or the bond's par value. For example, the face value of a catastrophe bond and resilience bond is usually 100 or 1000, and the value may differ from the bond's principal or purchase price.

- Discount factor: a weighting factor that transfers the future cash flow into the present value under the discount interest rate.

- Current value: current value refers to calculating the bond's future cash payments and principal into the value in the current time based on the up-to-date market interest rate.

- Spot rate and forward rate: a spot rate will be used to compute the instantaneous price of a contract, and the forward rate is used to calculate the settlement price, which will occur on the pre-determined date. Therefore, the forward rate will be calculated using the spot rate (i.e., yields on zero-coupon bonds).

- Zero-coupon bond: a zero-coupon bond pays no interest, and the bond purchase price at the initial period will be at a discount from face value.

After having examined the general structure and mechanism of a bond, project bond, green bond and catastrophe bond will be reviewed in the next sections. This analysis will be the foundation of the study of how resilience bond is structured (Section 2.4). A comparison analysis between catastrophe bond and resilience bond will conclude the chapter.

2.2 Fixed-income securities

2.2.1 The Project bond

Despite government enthusiasm for investing in infrastructure in recent years, public resources have become fewer and the public sector has increasingly sought new sources of project funding. According to Deutsche-Bank (2013), investment from the public sector has gradually been dwindling; huge debts and rising expenditures for infrastructure-related projects have challenged the public sector to reconcile its public spending. The World Economic Forum (WEF) has estimated that the shortfall in investment for critical infrastructure-related projects has exceeded about US$1 trillion every year (Caroline Miller et al. 2014). Therefore, governments and institutional investors are seeking to attract private investors to raise the needed funds for infrastructure-related projects (Orr and Kennedy 2008). Project finance is an alternative method for financing long-term infrastructure-related projects; it relies on project debt and equity to finance the project and receive payback from the operation of the project.

Traditionally, infrastructure-related projects are supported by banks, where commercial banks have funded almost 80% of project finance deals, even though capital markets are increasingly being adopted to raise capital (ibid.). However, banks must comply with the higher capital regulations in force through Basel II and Basel III, which reform and make uniform the international banking regulations by the Basel Committee on Bank Supervision. The stricter monitoring and disclosures have resulted in an increase in expenditures for project developers. Thus, the project bond is started to gain attention because project developers were potentially able to decrease their project costs via the capital market. The project bond market was developed in the early 1990s and the market has financed a variety of non-recourse basic assets, such as oil, gas, power. and infrastructure. Table 2-1 sets out the project bond by sector.

Table 2-1 Project bonds by sectors

Year	Total ($)	Sectors
1996	4.8 million	Power-2.6m; Petrochemicals-1.4m; and Infrastructure-0.8m
1997	7.5 million	Infrastructure-2.4m; Power-1.9m; Telecoms-1.3m; Oil & Gas-1.0m; and Mining-0.9m
1998	9.8 million	Power-4.5m; Telecoms-2.2; Oil & Gas-1.3m; Infrastructure-1.3m; and Mining-0.5m
1999	19.9 million	Power-7.2m; Telecoms-5.2m; Infrastructure-3.7m; Oil & Gas-2.8m; Petrochemicals-0.7m; and Leisure-0.3m
2000	20.8 million	Power-11.9m; Infrastructure-3.4m; Oil & Gas-3.3m; Telecoms-2.0m; and Industrial-0.2m
2001	25.0 million	Power-12.3m; Oil & Gas-3.8m; Infrastructure-2.3m; and Telecoms-1.5m
2002	13.8 million	Infrastructure-6.5m; Power-4.3m; Oil & Gas-2.6m; Industrial-0.3m; and Leisure-0.1m
2003	32.1 million	Power-12.3m; Infrastructure-9.8m; Oil & Gas-7.0m; Social Infrastructure-2.1m; and Telecoms-0.9m
2004	28.6 million	Power-11.4m; Infrastructure-8.0m; Oil & Gas-5.2m; Social Infrastructure-3.0m; Petrochemicals-0.7m; Mining-0.2m; and Industrial-0.1m
2005	27.5 million	Oil & Gas-9.7m; Power-7.3m; Social Infrastructure-5.0m; Infrastructure-4.4m; Mining-0.7m; and Petrochemicals-0.4m
2006	28.7 million	Oil & Gas-9.0m; Social Infrastructure-8.6m; Infrastructure-6.8m; Power-2.5m; Mining-0.7m; Petrochemicals-0.6m; and Leisure-0.5m

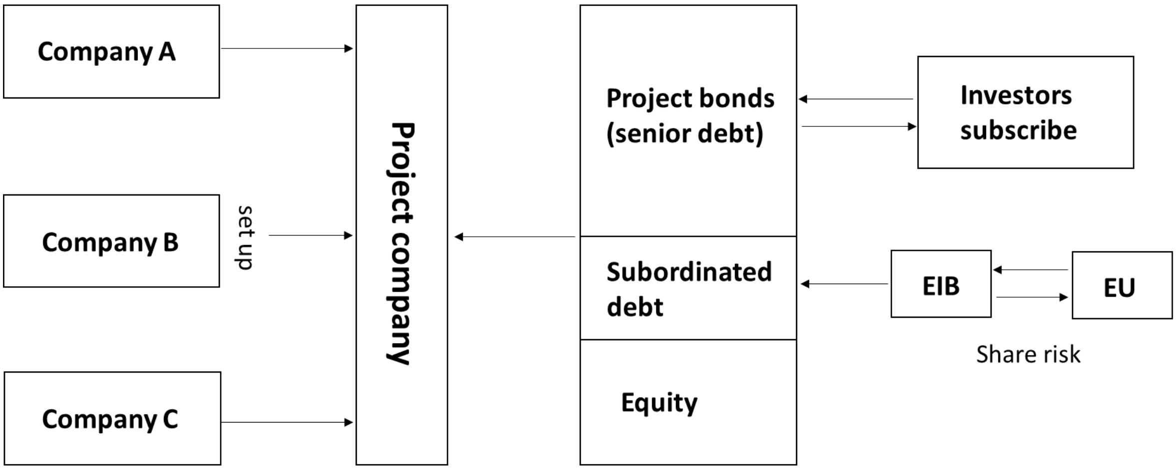
2007	26.8 million	Infrastructure-10.3m; Power-7.0m; Social Infrastructure-6.1m; Oil & Gas-2.1m; and Leisure-1.3m
2008	11.9 million	Infrastructure-6.9m; Oil & Gas-4.5m; Power-0.4m; and Mining-0.1m
2009	8.5 million	Oil & Gas-5.5m; Power-1.6m; Social Infrastructure-0.9m; and Infrastructure-0.5m
2010	19.8 million	Infrastructure-7.7m; Power-4.8m; Oil & Gas-2.5m; Social Infrastructure-2.2; Mining-2.0m; and Leisure-0.6m
2011	22.2 million	Infrastructure-6.0m; Power-5.5m; Social Infrastructure-5.3m; Oil & Gas-5.1m; and Mining-0.3m

Source: (Boudrias et al. 2012)

The project bond market is a new asset class to provide diversification of investment opportunities to institutional investors (Dailami and Hauswald 2003). The bond was developed by the European Commission and the European Investment Bank (EIB), and their main objective was to fund large-scale infrastructure-related projects in fields such as transport, energy, and information communication technology. The fixed coupon rate of the project bond is 11% over 15 years, and a modification can be made during year 7. Institutional investors like pension funds and insurance companies are the former holders of infrastructure-related project bonds. The Europe 2020 Project Bond Initiative (PBI) has been designed by the European Commission and EIB to attract private finance from insurance companies and pension funds to support eligible infrastructure-related projects. The bond is a debt instrument that can be issued by project companies and constitutes the public and private partnership (PPP) for infrastructure investments. Project sponsors will issue a project bond when an infrastructure-related project needs long-term debt with a fixed rate. Then the issuer will rate the bond by rating agent to attract investors with a flexible agreement (Boudrias et al. 2012).

Figure 2-1 shows the mechanism for a project bond. The issuance of a project bond is from a project company that may combine several companies. The project operating company will sign a long-term debt contract with the European Investment Bank and pay debt amortising accordingly. The default risk of project bonds is underwritten by specialist bond insurers because the EIB and EU will share the risk of the debt; the bond is guaranteed by the European Commission.

Figure 2-2 Project bond mechanism



Source: European Commission, EIB, DB Research schematic interpretation.

As the research from Deutsche-Bank (2013) shows, the public sector as one of the main capital sources for infrastructure development has accumulated a high debt after the 2008 financial crisis, which brought severe impacts to traditional funding instruments and led banks to increase stricter requirements for lending money. However, the project bond has become a new alternative funding method for financing infrastructure-related projects. Sawant (2010) states that infrastructure-related project bonds are different from other options such as stocks and syndicated loans for procuring infrastructure exposure. The main object of the bond is to attract private investment and raise money from the capital market to cover the infrastructure-related projects' fund gap.

The project bond initiative was created to attract private investors and institutional investors involved in the eligible infrastructure-related projects. Caroline Miller et al. (2014) prove that project bonds are offering long-term investors attractive yields and significant credit spreads. The stability and long-term scale of the returns are suitable for investors like pension funds and governments. Hence, project bonds in Europe have been recognised as a substitution for long-term debt from banks. However, project bonds may contain some drawbacks, such as a complex structure, and the payback will only be received upon completion of infrastructure-related projects. The structure of the project bond involves different entities and specialties, including public sectors, investors, regulators, operating firms, capital market specialists, and banks. Therefore, the discussion of the bond may last longer. Indeed, project bonds are suitable for large-scale projects (in excess of 300 m. pounds), long term project, operating projects, and highly rated projects (Boudrias et al. 2012). Bigger deals make it much more difficult to obtain long-term lending from banks. But bond investors may feel more inclined to get involved in larger deal investments (Euroweek 2013). Nevertheless, companies can potentially reduce the project funding cost by accessing the project bond market.

Although project bonds are mostly used in America and Europe to finance infrastructure projects, the bond has also been successfully implemented in Kenya and Nigeria. Kenya in particular has offered a tax exemption for infrastructure-related project bonds to encourage the use of the bond. The Kenyan public sector has turned to the capital market to diversify investments even though there is sufficient public money. In recent years, project bond has brought benefits to many projects. For instance, according to Caroline Miller et al. (2014), the A-11 motorway construction in Belgium is the first Project Bond Credit Enhance (PBCE) in a greenfield context, which is mainly invested by the European Investment Bank (EIB) and Allianz Global Investors. The project is one of Belgium's largest Design-Build-Finance-Maintain projects.

2.2.2 The Green bond

The green bond is a fixed-income financial instrument designed to raise money from the debt capital market for climate and environmental benefit projects. Hodgson (2021) shows that the processes to issue a green bond requires fulfilling the four core Green Bond Principles, which are 1.) identify definitions and standards for the purpose of using the funds, 2.) process an assessment and selection to the project, 3.) manage the process to be trackable and attestable, and 4.) provide a report at least annually. A green bond is similar to other bonds in that the bond issuer raises a fixed amount of capital from bond investors over a set period of time. Next, the bond investors will receive back the capital at the maturity of the bond and gain an agreed amount of interest regularly. The unique feature of the green bond among the bond market is the commitment to use the fund to finance or refinance 'green projects', assets or business activities (OECD 2017). A report from KPMG (2015)states that the green bond mechanism of raising capital for ‘green’ projects, assets or other activities that benefit the environment, economy and society, is getting popular among the organisations from both the private and public sectors.

As a fixed income debt security, the green bond is fundamentally similar to other types of loans and debts, and municipal governments are one of the most typical issuers of the green bond as its investment vehicle in green projects (Tolliver et al. 2020). In most cases, the green bond has been used to raise funds for municipalities to finance infrastructure projects that bring positive impacts to local communities. According to Cestau et al. (2019), green municipal bonds are an innovative way for municipalities to develop green projects that have been recognised as ‘responsible investments’ that ‘specifically target socially-conscious investors.’ The bond has helped to unlock finance for investment in green projects in renewable energy, public education facilities, and social infrastructures. Saha and d’Almeida (2017) show that the market of green municipal bonds is expected to expand with diversified buyers in the environment, social, and governance (ESG) investment market. Fulfilling the ESG criteria are an efficient screening for investments which are likely to stimulate the growth of the green bond market. As stated in Cestau et al. (2019), municipal bonds are a responsible investing strategy that have a history of delivering social benefits with high credit ratings and low default rates. The issuance of green municipal bonds will give credibility to socially conscious investors within the municipal bond market.

The first green bond was issued by the European Investment Bank (EIB) in 2007, and the market soon was burgeoning and attracted many issuers, such as sovereigns, supranationals, corporations, and international municipalities (Baker et al. 2018). For example, Tang and Zhang (2020) report that Poland issued its first green sovereign bond in December of 2016, followed by France in January, 2017. Malaysia soon followed, issuing the world’s first green Islamic bond (‘green Sukuk) in June of 2017, which was specially designed for climate-resilient growth projects. According to Almeida (2020), the year 2019 witnessed a significant rise in the green bond market; green loan issuance has reached a new global record at USD 258.9 billion which increased 51% in 2018 outstanding. The rapidly growing green bond market has provided sufficient progress in supporting the development of environmental-related projects.

Green bonds have some potential benefits that allow them to grow fast in the market and consequently help to increase the capacity of capital available for green infrastructure projects. As stated in KPMG (2015), green bonds show more advantages in attracting investors from a broader range than do regular bonds. The mechanism of green bond has tied the repayment of capital to the issuer instead of the completion of the project, which has a lower risk of default in returning the capital to investors at maturity. This design is attractive to new investors, particularly the environmental, social and governance (ESG) investors who seek positive returns and long-term impacts on society. However, Sartzetakis (2020) argues that the loan from the application of green bond is used to invest in environmental projects which will benefit the next generation; therefore, the current generation should release some of its burden and consider stretching the repayment of the loans to future generations. Another key advantage is that issuing green bonds will enhance the reputation and visibility for the issuer who desires to support the development of climate-change projects (Hodgson 2021). Moreover, KPMG (2015) show that the issuance of green bonds will effectively establish the green credentials for organisations to perform their commitment to helping with the environmental improvement projects. Green bonds increase the awareness of the organisation and improve the attractiveness between finance and sustainability professionals. However, Bachelet et al. (2019) argue that the green bond issuer may also face reputational risks if a labeled project is fraudulently 'not green' and thus loses the trust of its investors. Therefore, rating agencies have included the assessment of 'greenness' in financial projects that assist investors in portfolio investment selection. There are also some concerns emanating from the market participants. For instance, according to an OECD report OECD (2015a), the Deutsche Bank, Global Capital and Institutional Investor have pointed out that the growth of potential critical sources of capital for the development of infrastructure projects, such as low carbon and climate-resilient (LCR) projects, may be delayed, inhibited, or derailed in the early stages due to the process of qualifying a project as 'green'. For instance, as the largest regional public transportation provider in the Western Hemisphere, the New York Metropolitan Transport Authority (MTA) issued a Transportation Revenue Green Bond in 2016 (series 2016A). The size of the bond is $782 million and was issued especially for the low carbon transport development, which was approved by the Climate Bond Standard Board, (New-York-Metropolitan 2016).

2.3 Insurance-linked securities

2.3.1 The Catastrophe bonds

In order to avoid unpredictable economic losses, most entities choose to enter into the insurance market to seek financial coverage from insurance companies (insurers). An insurance contract will move the catastrophic risk from entities to insurers by means of pre-defined trigger conditions. As shown in D. Wu and Zhou (2010), many insurance companies have in recent years played an important role as insurers to propel catastrophe risk-linked insurance services to hedge catastrophe financial losses. The CAT bond has played an essential role in the risks exchange between businesses and capital market investors; it combines financial instruments with insurance via an intermediary (re)insurance company through a risk diversification mechanism, (J. D. Cummins and Weiss 2009; J. D. Cummins and Trainar 2009). However, insurance services may lead the insurer to exposure to unpredictable risks in the meantime. Therefore, most insurance companies jump into a reinsurance contract with bigger reinsurance companies (cedant) in order to share the risk due to the large capacity to handle more risks and losses. some cedants are involved in unforeseen uninsurable mega-catastrophes, which has a low probability of occuring, but once it does occur will lead to huge consequences. Catastrophe bonds can be a popular creation that transfers the risks from cedants to the more capable capital market to avoid bankruptcy. Table 2-2 lists the top 10 sponsors and cedants.

Table 2-2 Catastrophe bonds & ILS top 10 sponsors and cedants

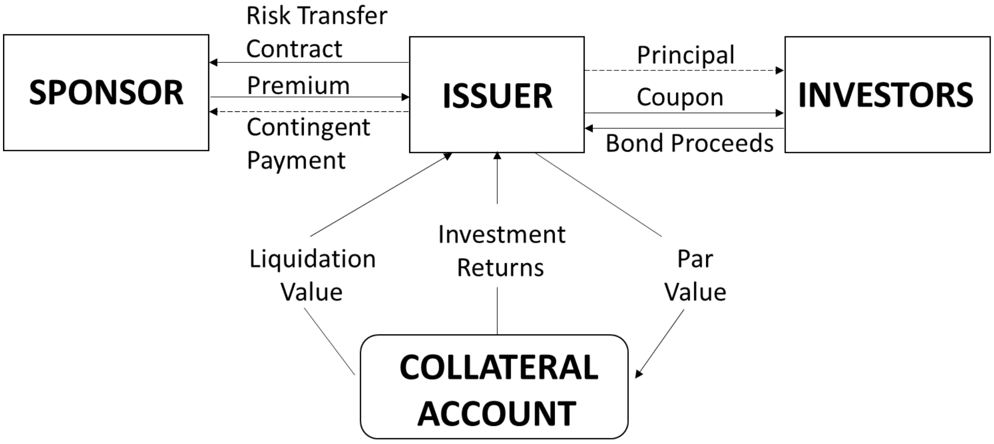
Sponsor or cedant	No. of deals	No. of tranches	Total outstanding $million
Arch Capital Group	8	33	4,152.1
Everest Reinsurance Company	6	14	2,625
California Earthquake Authority	4	6	1,975
Zenkyoren	3	6	1,900
USAA	6	16	1,880
Essent Guaranty	4	16	1,727.4
Radian Guaranty	3	12	1,484.5
Allstate	4	4	1,375
XL (Catlin)	3	11	1,350
FEMA/NFIP via Hannover Re	3	6	1,200

Source: ARTEMIS (2020).

Canabarro et al. (2000) define the catastrophe (CAT) bond as Insurance-Linked Securities (ILSs), which provide exposure to catastrophe risks by issuing bonds with coupon payments on contingent disasters. CAT bond (or ‘Act of God bond’) is a liability hedge instrument and offers a high yield to investors as risks financing solutions for business’s catastrophic losses. According to J. D. Cummins (2008), the CAT bond is a common financial vehicle for (re)insurers to back up the traditional insurance and reinsurance market as supplementary. This innovative creation has been widely applied by (re)insurers to reduce default risks and transfer the risk to capital market investors (Vaugirard 2003). The very first catastrophe-linked securities appeared on the market after the Hurricane Andrew disaster in 1992 (Bouriaux and MacMinn 2009). Soon afterward, the CAT bond was issued the first time in 1994 and then gained a boost in 1997.

Figure 2-2 illustrates the mechanism of a catastrophe bond, the traditional CAT bond in which the capital flows between sponsors and investors. In order to hedge the unforeseen losses, entities will seek protection from the sponsor, then the issuer will issue a CAT bond for the sponsor and sell the bond to investors to raise a ready-for-reimbursement principal in a collateral account. The principal will only be invested in the highly-rated market such as Treasury Bonds (T-Bill), (J. D. Cummins 2008). Sponsors are (re)insurance companies that offer insurance services to businesses to cover the post-catastrophe financial losses. The issuer will be a special business entity, also called a special purpose vehicle (SPV), which responds to the issuance and sells the bond to the capital market. Meanwhile, the SPV receives bond credit ratings from rating agencies such as S&P and Fitch, where the CAT bond is rated at BB level. Investors interested in CAT bond investments are normally pension funds, mutual funds, hedge funds, and commercial banks (Willis 2015). The (re)insurance company needs to pay a premium to the SPV and enter into a risk transfer contract to pre-define the specific trigger event and trigger level. On another side, a coupon payment is paid to investors semi-annually or annually, based on the contract. In recent years, the bond has begun to extend beyond protection in natural perils, which include risk coverage against power failures, cancellation of sporting events, epidemics, and acts of terrorism.

Figure 2-3 Catastrophe (CAT) bond mechanism



Source: (ARTEMIS 2021).

However, the UK Financial Conduct Authority (FCA) has announced that the GBP LIBOR-linked loans, bonds, securitisations and linear derivatives ceased from the end of 2021. In this study, LIBOR will still be used as an index to simulate the stochastic interest rate. There is some alternative index can be applied to replace since LIBOR is retiring at the end of 2021. There are currently some replacements have been considered, for example, International Swaps and Derivatives Association (ISDA), the Sterling Risk Free Rates Working Group (RFRWG) and Sterling Overnight Index Average (SONIA). Table 2-3 shows the outstanding of catastrophe bonds.

Table 2-3 Catastrophe bond & ILS risk capital issued & outstanding by year

Year	Issuance (millions)	Outstanding (millions)		2008	Issuance 2,795.27	Outstanding 14,383.17
1997	785.50	785.5		2009	3,211.26	13,904.91
1998	1,289.78	1,595.28		2010	5,446.92	13,873.08
1999	1,068.85	1,892.03		2011	4,969.52	14,448.3
2000	1,176.10	2,806.13		2012	6,309.86	16,872.46
2001	1,283.90	2,858.35		2013	7,667.94	20,754.73
2002	1,396.45	3,760.95		2014	9,094.07	25,279.57
2003	2,294.48	5,235		2015	7,898.18	25,960.45
2004	1,142.8	5,201.23		2016	7,052.70	26,819.90
2005	2,489.12	6,599.5		2017	12,560.00	31,036.00

2006	4,694.55	9,165.65		2018	13,860.2	37,550.1
2007	8,293.73	15,877.13		2019	11,094.4	40,685.4

Source: ARTEMIS (2020)

The general maturity of a CAT bond is 3- to 5-years; the principal will be returned to investors if no catastrophic events have occurred during the maturity period. The return for a catastrophe bond will follow the floating London Interbank Offered Rate (LIBOR) coupon plus the premium at a rate between 2% to 20%. According to the ARTEMIS report, annual returns of U.S. hurricane bonds rose to 6.97% and U.S. earthquake bonds rose to 4.95% by Aon Securities in 2017. However, under special circumstances, a severe downside loss can wipe out the entire principal, and the obligation as an issuer to pay a premium and/or reimbursement of the principal from insurance company will be forgiven or deferred. Besides, Lee and Yu (2002) specify that a pre-defined contract to issue the catastrophe may benefit (re)insurance sponsors, because the bond will provide more liquid funds from the capital market for to avoid default risk when a mega-catastrophic event hits.

- **Examples of Catastrophe bonds**

The CAT bond is a popular bond used to hedge unpredictable catastrophe risks. However, as Re:Focus (2015) shows in their report, the CAT bond does have some disadvantages which may influence its expansion. For instance, the price of the bond fluctuates based on investor demand. As the final risk bearers, investors react by being less attracted to the bond because they face a higher risk of losing all or part of the principal when a catastrophe occurs. In addition, the CAT bond will only cover the post-catastrophe financial losses, rather than help with the physical development of the society.

The American Strategic Insurance Group issued a catastrophe bond via Bonanza Re Ltd. in February of 2020. The Bonanza Re catastrophe bond covers the entire United States for named storms, wildfires and earthquakes for a period of four years. The final size of the bond is $100 million, which will be sold to capital market investors and CAT bond funds. The initial attachment probability and expected losses are 1.15% and 1.03%, and the bond will be priced in the range of 4.25% to 4.75% (Artemis 2020). FloodSmart Re Ltd. issued a new catastrophe bond with FEMA/NFIP as the sponsor, via Hannover Re, in February of 2020. This CAT bond covers flood risks from named storms in the United States, and the size of the bond is $400 million. There are two tranches, the first of which is $200 million target issuance of Class A with lower risk, and the second is $100 million issuance of Class B with higher risk. The initial expected loss of Class A is 3.91% and 5.68% for Class B. The coupon rate may fall between 10.75% and 11.5% for Class A and between 13.75% and 14.5% for Class B. Successful issuance of the bond will lead to $1.1 billion benefits to the Federal Emergency Management Agency (FEMA).

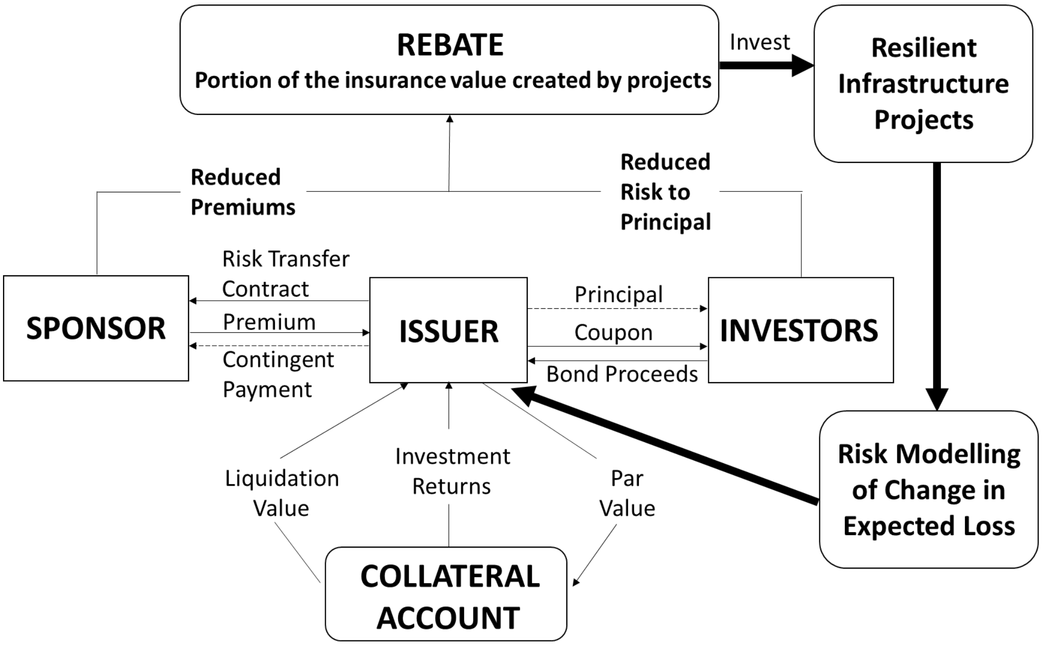
2.4 The Resilience bond

A resilience bond is a newly published bond in 2015 with a similar design to a catastrophe bond, which is a loan given to the issuer by investors who are expected to receive a fixed interest return. A resilience bond contains three main functions: 1. insurance, 2. rebate and 3. resilient project.

1. The insurance function of the resilience bond is, accordingly, designed like the conventional CAT bond. As per SwissRe (2016), any specific catastrophic events will be pre-defined in the insurance contract based on terms and conditions. If there is no covered catastrophic event that happens during the resilience bond maturity, investors will redeem full principal plus coupon payment and the insurance company will receive a premium from the insured entity. However, if the contract mentioned catastrophic events do occur, the raised principal will be reimbursed to the insured entities via sponsor immediately and investors will lose part or full principal accordingly. 2. Different from a CAT bond, the resilience bond offers a unique function, a 'rebate', which generates the upfront funds to invest in a resilient project. The mitigated cost and risk from the resilient project will be quantified into funds, known as the 'rebate', and backflow to support the project. This feature brings physical support to the development of resilience rather than paying for the aftermath, or placing a hold on a project due to lack of funds (Re:Focus 2015). 3. Resilience bonds emerged from a need for resilience, hence, the bond aims to support physically resilient projects which can mitigate risks thus achieve resilience against unpredictable events.

Figure 2-3 shows the mechanism of the resilience bond. The fundamental function is the insurance protection. The mechanism for this function is similar to CAT bonds, where sponsors pay a premium to the issuer for the exchange of financial protection from unforeseen catastrophe losses. Then, the issuer will issue and sell the resilience bond to capital market investors to raise the ready-to-reimbursement funds. According to Vaijhala and Rhodes (2018), on top of the conventional CAT bond mechanism, a resilient infrastructure project will be proposed to improve the resilience of the related system. A third-party evaluator will assess the project by forecasting and transferring the reduced risk into a deduction of premium and principal in 'rebate' form. Consequently, this 'rebate' can be used as an upfront cost for the project or as the maintenance and operation cost. For a resilience bond, the sponsor can be an entity such as an insurance company, which is interested in resilient infrastructure projects and creates demand for security for the project during the construction period. The issuer is a reinsurance company and most common investors can be pension funds, mutual funds, hedge funds, and commercial banks (Willis 2015). The issuer will issue the bond via Special Purpose Vehicle (SPV) and the SPV will enable the bond to receive credit ratings from rating agencies.

Figure 2-4 Resilience bond mechanism



Source: RE bound insuring for resilience report 2015.

According to Re:Focus (2015), the resilience bond contains several characteristics:

1. Entities in resilience bond

The sponsor of resilience bond can be a single entity or multiple cooperation partners who are willing to purchase insurance services and provide investment funds for resilience projects. Unlike municipal bonds and corporate bonds issued by the sponsors, resilience bonds can only be issued by the issuer, which is an intermediary SPV. The SPV can be an agent or investment bank that issue the bond and sell the bond in financial market investors. The investors can be both private or public investors, such as insurance company or pension funds. The obligation of the sponsor is to pay the premium to the issuer and receive reimbursement once the pre-defined catastrophe occurs. The unique function of a resilience bond is that the sponsor can receive a rebate, which is a portion of the insurance value created by the resilience project. In addition, like the insurance purchase, resilience bond sponsors are only dealing with premium payments to issuers instead of paying the principal back to bond investors after the bond reaches maturity. Investors will receive coupon payment based on the purchase of resilience bond, besides, the investment in resilience bond will receive high returns if no catastrophe occurs during the bond maturity. However, the investors may also lose partial or full principal if a catastrophe occurs.

2. Collateral Account

The maturity of resilience bond is coordinated with the project development timelines and milestones. During the maturity, the principal received from bond investors will be saved in the collateral account, which is a safe account and only invest in stable financial products, such as the U.S. treasury bill.

3. Rebate Mechanism

Resilience bonds can be applied by using rebates to capitalise on resilience programs, such as strengthening disaster response by building infrastructure-related projects. The bond generates rebates from the reduction in bond coupons and premiums, which are based on third-party anticipation of the risk mitigation created by the resilience project. In addition, there are two criteria that should be pre-defined within the rebate mechanism, that is, who will receive the rebate funds and how to manage rebate funds within a resilience bond program. The use of rebate funds can be segmented in different ways. It can be used to fund the upfront cost of resilient infrastructure projects. Or they could be used to reduce the insurance service cost.

Finally, rebate funds could be used to increase the insurance coverage for the resilience project. However, rebate funds can also be used to advance resilience projects in different ways. A resilience bond is typically issued by insurance companies to cover the risks for resilient infrastructure projects with a predetermined period. It provides rebate and post-disaster reimbursement.

4. Resilient Infrastructure Projects

Eligibility projects should accord with two requirements and should be defined at the beginning of the bond issuance. Firstly, the potential project can reduce the risk of failure for the whole system, which will generate rebates within the resilience bond program. Specific projects with the location, funding source, and construction date should be defined in the contract. Secondly, the project parameter should be defined to quantify the reduced risks , then, transfer the reduced risks into a reduction to the premium and bond coupons. This thesis has tested two type of infrastructure projects which can reduce the risk of failure to the whole system, such as an intermodal transport port and enhancement of flood defence projects.

5. Risk modelling

These projects will be qualified by reducing risks and producing potential rebates based on risk modelling from the third-party evaluator. An appropriate risk modelling plan should not only satisfy the insurance needs of sponsors, but also satisfy information needs for bond investors. Data for sponsor exposures, resilience bond structure and expected risk reductions from the resilience project should also be provided. The risk reduction in resilience bond coupons will be defined as a dividend or rebate.

- **Examples of Resilience bond**

Resilience bonds have been applied to support different resilient projects and hedge variable risks, particularly in regard to climate change and its foreseeable impacts. The changing of climate from shifting weather patterns to heightened catastrophe risks, is a global issue for human beings nowadays. In one of the actions being taken to solve the issue, the European Bank for Reconstruction and Development (EBRD) has launched a climate resilience bond successfully; it has been rated by AAA and raised $700 million to support climate-resilient projects such as climate-resilient infrastructures, climate business and operations or agriculture and ecological systems. The demand for the bond is increasing and at present includes almost 40 investors from 15 countries (Bigoni 2019).

Blue Forest Conservation proposed a Forest Resilience bond (FRB) across the Western U.S. in 2016 and the bond was officially published in 2018. The design of an FRB is a public-private partnership, which enables private capital to finance the resilient infrastructures to protect the forest. The main purpose of the FRB is to mitigate wildfire risk and enhance water security by contracting with public and private beneficiaries to monetise the multifaceted benefits of forest restoration (Blue-forest-conservation 2017). The market opportunity is expected to be $3.5 billion/year and the potential scale of intervention will be $529 million/year.

Texas cities and other states are officially cooperating with private investors on the Ike Dika project via applying for a resilience bond. Private companies such as railroads and the oil and chemical industry have purchased resilience bonds instead of traditional insurance because the company's assets are exposed to flood risk. As a result, US 15 billion dollars will be raised from private companies for the project to fortify seawalls and floodgates against storm and flood damage (Kaskey 2018).

2.5 A comparison discussion

Bonds are recognised as an efficient tool to lever more private finance involvement in the investment for infrastructure-related projects, thus constituting a public-private partnership (PPP) model. In this section, we compare four reviewed bonds and analyse the optimal bond to support the development of resilient infrastructure projects. Project bonds have been widely adopted in the EU as a debt instrument to stimulate the capital market to finance large-scale infrastructure-related projects. Green bonds are popular in the United States and China for financing climate change-related infrastructure projects. The bonds not only provide a good opportunity to attract private finance but they also have become a major link between private debt and long-term economic growth. The catastrophe (CAT) bond is a financial vehicle which provides the opportunity to sell insurance risk to the capital market for insurers and reinsurers to raise funds for losses due to catastrophic events; it is widely adopted to hedge against catastrophic financial losses. Resilience bonds are a newly proposed type of bond; they contain similar functions as both project and CAT bonds. Resilience bonds will advantageously generate rebates for a resilient infrastructure project and insurance protection for the project against post-catastrophe financial losses.

When we compare the four bonds, the project bond is seen to be specially designed for all projects instead of only infrastructure development. However, there are also some limitations for the application of project bonds. For example, project bonds are being restricted in the market except Europe. Therefore, the green bond and the resilience bond are the only two bonds with the function of providing investment funds for a global climate-change orientated infrastructure project. A green bond can be issued by the promoter of the green infrastructure project to raise funds during the infrastructure's lifetime. On the contrary, a resilience bond can be issued by an insurance company that is interested in resilient infrastructure projects and looking to hedge the future unexpected economic losses from catastrophes. It is not hard to discover that the green bond has the advantage of offering more capital for the infrastructure project than a resilience bond. According to Re:Focus (2015), the rebate from a resilience bond will be generated from forecasting by a third-party evaluator, who will assess the risk mitigated from the resilient infrastructure project, then transfer the reduced risks into a deduction of premium and principal in rebate form. Both green bond and resilience bond are only designed based on eligible projects, which means the project must be specifically 'green' or 'resilient.' However, the additional condition of applying a resilience bond is that the infrastructure has the potential to generate rebates, which has restricted the range of bond investors only to those who are interested in investing in real protection infrastructure against physical risks, e.g., seawalls and flood barriers. As Dailami and Hauswald (2003) show, the volume of capital raised from international project bonds is still relatively small. Although green bonds can offer more funds for the resilient infrastructure projects, it has ignored the emergency maintenance cost from catastrophic events. Croson and Richter (2003) have demonstrated that insufficient emergency maintenance funds will generate extra expenditures over and above the damaged value to the project itself. For example, a roof may need to be installed immediately for a nearly finished school after a hurricane; otherwise, the extra cost of the project will be generated by the continuous damage. Nowadays, governments are becoming more aware of disruptions at both the national and project level; therefore, governments around the world are seeking financial protection from the insurance industry so as to avoid disruption. Dollery et al. (2007)

argue that infrastructure maintenance and renewal have brought a heavy burden to the public sector due to the distressed financial situation.

In the research of Croson and Richter (2003), if an unexpected catastrophic event occurs during the construction period, the project has two options, to fail and start over, or use future cash flow to cover current financial losses. Under these circumstances, the CAT bond would be the first choice for promoters and investors because the use of the future cash flow will influence the follow-up phases of the project. The CAT bond offers post-catastrophe reimbursement to provide financial reimbursement in case a catastrophe occurs. However, CAT bonds may only mitigate the risks of aftermath financial consequences and indirect impacts rather than reduce the physical risks for the infrastructure systems (Re:Focus 2015). The Institute-for-government (2018) suggests that public investors may not prefer to start investment on an infrastructure-related project if there is no clear funding stream because it is difficult to use the restricted public resources without stable upfront capital for long-term maintenance and operation costs. This points to the importance of upfront costs from private finance for an infrastructure-related project as adequate funds will increase the probability of attracting more investors to contribute to the development of infrastructures.

Our comparison of the resilience and CAT bond reveals that both bonds have the same insurance function for post-catastrophe losses, but the resilience bond can offer an additional 'assessment of risks' rebate as the upfront cost for an infrastructure-related project. Like the CAT bond, the resilience bond does not correlate with the wider economic environment, because the two bonds are only triggered by actual catastrophic events. The resilience bond is also more appealing to private institutional investors such as insurance companies and institutions as an investment. In addition, the principal of both CAT and resilience bond will be saved in a collateral account and invested in the U.S. treasury bill to ensure its availability for reimbursement. The difference is that the resilience bond explicitly measures and reduces the expected losses from investors to the resilient infrastructure project. Transitioning from CAT to resilience bond can bring additional rebate funds for the project promoter to reinvest into physical protection construction as well as financial protection for the project. However, the limitation of the resilience bond is that, to be eligible, it must generate rebates, which means that the project must bring resilience and reduce risk for the infrastructure system.

In order to analyse which bond can be the optimal tool in support of resilience infrastructure projects, we compare and analyse the effects of different bonds in different stages of the project. In this way, we follow Ehlers et al. (2014) to divide the infrastructure project into three phases of planning, construction and operation.

1. Planning phase

At the beginning of an infrastructure-related project, the application of Project bonds such as green bonds and resilience bonds may be significantly more attractive to investors than CAT bonds. According to (Institute-for-government 2018), a clear arrangement of project funding will unlock more investment capital to contribute to improving infrastructure development. Institutional investors are willing to cooperate with private investors in the capital market. Project bonds and green bonds ensure the project with sufficient funds in advance for the whole construction when planning an infrastructure-related project, and are likely to attract more investors than the resilience bond. As previously discussed, the resilience bond shows less attractiveness in the planning stage due to complex mechanisms and additional costs for the third-party evaluator. In brief, investors are willing to invest in infrastructure-related projects with a clear funding stream at the planning stage.

2. Construction phase

Catastrophes such as earthquakes and floods are low probability and high consequences events, which can cause preoccupy investors who are concerned about the completion of infrastructure projects. In the construction phase, we follow the assumption of Croson and Richter (2003), which is to assume that an infrastructure-related project has two construction phases. Consequently, there will be four situations:

- The emergency repair will be implemented only in the first construction phase.

If the infrastructure-related project is applying a project bond and green bond as financial resources, an emergency repair can be done by using the funds from the second phase in advance, which could lead to insufficient funds for follow-up construction. In contrast to a resilience bond, an emergency repair can be carried out by using the reserved principal, which will not influence the construction fund in the second phase.

- The emergency repair will be implemented only in the second construction phase.

Under this circumstance, the project will be failed or restarted because the first construction phase is the foundation of the second phase.

- The emergency repair will not be implemented in any of the construction phases.

Since catastrophes are low probability and high consequence events, some investors may be concerned about the risks and reject their involvement in the infrastructure-related project in the planning phase.

- The emergency repair will be implemented during both phases one and two.

Preparedness for an emergency repair throughout the whole process of construction for an infrastructure-related project will require that the project hold ample liquidity, due to the unpredictability of catastrophic events. Both public and private investors will not prefer to invest extra capital due to funding pressures and tax and accounting issues. In this circumstance, CAT bonds and resilience bonds can be adapted to benefit the project by providing catastrophe financial protections via insurance and reinsurance companies. Meanwhile, the resilience bond is more competitive because it can offer additional upfront capital for the emergency maintenance cost. In summary, during the construction phase, a resilience bond shows its advantage by offering two functions: the upfront fund and financial protection. If the project fulfils the requirements of the resilience bond program, the resilience bond will be the default choice. Otherwise, project bonds and green bonds have a strong advantage in supporting the financing of infrastructure.

3. Operation phase

According to Carreras and Kara (2017), construction of infrastructure-related projects tends to enormous amounts of upfront costs, and the payback will accrue over a long period. After construction of the infrastructure-related project is complete, investors may start to procure benefits from the operation of the infrastructure. However, the infrastructure remains exposed to physical risks brought about by catastrophic events since even a small disruption may lead to ripple effects in the infrastructure’s operation. (H. C. Kunreuther and Linnerooth-Bayer 2003) discuss how the increasing frequency and severity of catastrophe events is motivating many countries to adopt hedging instruments to transfer and manage risks. The CAT bond is one of the most popular methods for allowing investors to transfer the risk to the capital market to gain financial protection from a catastrophe. However, sponsors will receive additional value by transitioning from CAT bond to resilience bond if the infrastructure-related project is eligible for generating rebates within the resilience bond program. The additional rebate generated from the resilience bond can be used for further operation costs, even though the project has enough funds for the construction. In short, for an infrastructure-related project that is ineligible for a rebate, the CAT bond is a suitable financial tool against catastrophe risk in the operations phase. Otherwise, resilience bonds have more advantages in resilient infrastructure projects.

The aforementioned four bonds have different effects on each stage of an infrastructure project. It is also important to mention that different infrastructure markets may also influence promoters' decisions. The project bond and green bond are more attractive in the planning and construction stages; however, the project bond is adopted more in the Europe market and the green bond is restricted to the build of green infrastructures. We have shown that the CAT bond is more useful at the operational stage since unpredictable catastrophes are sudden events that may bring significant financial losses. Project bonds and the green bond can attract private finance to release the pressure on public resources because public funding for infrastructure-related projects normally comes from taxes or charges. The CAT bond creates an opportunity for the infrastructure project to reduce financial losses from catastrophes, but it may only reimburse the aftermath of financial losses instead of supporting the development of resilience to the infrastructure system as a whole. On the contrary, if the infrastructure project can mitigate the catastrophe risks for the whole infrastructure system, such as flood barrier, seawall and intermodal transportation port, the resilience bond will be the first choice for promoters. By applying a resilience bond, the resilience project will receive not only upfront capital, which is assessed by the third-party evaluator from the risk mitigated from the infrastructure, but also insurance financial protection for the project in all phases. Resilience bonds can allow investors to transfer risk to the capital market to gain financial protection from catastrophe; they offer a high yield, and the operation depends only on the occurrence of catastrophic events, which can reduce moral hazard.

2.6 Summary

This chapter has reviewed the financial tools associated with infrastructure investment and has introduced the mechanisms of the most popular used fixed-income securities and insurance-linked securities: Project bond, Green bond, Catastrophe bond, and Resilience bond. From the review, we found that fixed-income securities mainly focus on raising an investment fund for infrastructures, rather than responding to post-catastrophe rebuild or recovery. The project bond is mainly applied in EU countries that are specially designed to raise capital for infrastructure projects. However, the project bond is mainly used in large-scale infrastructures, such as transportation and energy rather than the relatively small resilient infrastructure projects flood defense enhancement and intermodal hub upgrade, etc. Whereas the green bond reviewed here has been shown to be largely applied in environment-related 'green projects,' and the issuance of the green bond for a project is based on being assessed as 'green.' On the contrary, the catastrophe bond was designed specifically to raise the ready-to-use funding for post-catastrophe reimbursement. However, these bonds all function within a single aspect in the development of infrastructure instead of considering both financing and hedging infrastructures from unexpected catastrophes. In response, the review has compared the above-mentioned bonds with the newly published resilience bond, which shows comprehensive functions in both financing the resilient infrastructure projects and providing insurance protection. After our comparison discussion, we have reached the conclusion that fixed-income securities are effective in raising funds for large-scale infrastructure projects, but not efficient for the increased risks from the failure of infrastructure. Therefore, an application of a resilience bond may benefit infrastructure development, especially in the resilience context, by providing both financing and insurance functions.

Chapter 3 Valuation Methodology

3.1 Preliminary bond valuation

The bond valuation is a package of calculations, including future coupon payments and principal repayment (Brealey et al. 2012). When pricing a bond, the future coupon payments and principal need to be transferred into the current value by considering the discount factor. Therefore, investors may purchase a bond in three situations: when the bond's current value is below face value, when it is above face value, and when its current value is equal to face value. To price a bond, the present value of the bond's coupon payments and face value need to be calculated and are known as the 'current price' of the bond. The discount factor will be applied to measure the current value received in future years. The price of the bond is inversely correlated with the yield of the bond:

- If yield > coupon rate, current price < face value
- If yield < coupon rate, current price > face value
- If yield = coupon rate, current price = face value

Calculating the value of a bond at the initial time is essential for both issuers and investors in the financial market. Two parts are involved in the calculation; they are the present value of the bond's future coupon payments and the present value of the bond's face value. To calculate the present value of the bond's future coupon payments:

$$\begin{aligned}\mathrm{PV}_{coupons} &= \frac{C_1}{(1+y)^1}+\frac{C_2}{(1+y)^2}+\frac{C_3}{(1+y)^3}+\cdots+\frac{C_T}{(1+y)^T}\\ &= \sum_{t=1}^{T}\frac{C}{(1+y)^t},\end{aligned}$$

where

$\mathrm{PV}_{coupons}$ is the present value of future coupon payments;

t = 1,2,3 … T, where T is the number of periods until the bond's maturity date;

C_t is the discounted value of the cash flow;

y is the yield to maturity.

The present value of the bond's face value is calculated as:

$$\mathrm{PV}_{face\ value} = \frac{F}{(1+y)^T}$$

where
$\mathrm{PV}_{face\ value}$ is the present value of the face/par value;
F is the face/par value.

We calculate the price of a bond to be equal to the sum of the current value of its expected future coupon payments and principal, as follows:

$$\mathrm{P}_{bond} = \mathrm{PV}_{(\text{ future coupon payments})} + \mathrm{PV}_{(\text{future principal})}$$
$$= \sum_{t=1}^{T} \frac{C}{(1+y)^t} + \frac{F}{(1+y)^T}$$

For simplicity, the price of a bond is generally calculated as a zero-coupon bond which makes no coupon payments. The bond will be traded at the initial period with a deep discount from face value instead of coupon payments. Investors will thereafter receive a return at the bond's maturity with a face value.

A zero-coupon bond is priced as follows:

$$\mathrm{P}_{bond} = \frac{F}{(1+y)^T}$$

In this thesis, we focus closely on the valuation method for catastrophe (CAT) and resilience bonds. In the real market, the pricing method of a catastrophe bond and resilience bond is more complex than the generic bond valuation method. Catastrophe and resilience bonds are the type of risk-linked bonds which transfer the risks of catastrophic events to capital market investors. In addition, a resilience bond has a unique function -- which is to consider a deduction of risks from resilient infrastructure projects. Therefore, the valuation of a catastrophe bond will be calculated as the combination of zero-coupon bond value plus the dynamic process of interest rate and claims. Furthermore, a resilience bond will be priced based on the design of a catastrophe bond by considering the resilience level generated from a resilient infrastructure project.

3.2 Catastrophe bond valuation

As a financial instrument, the catastrophe (CAT) bond was created to hedge unpredictable catastrophic events and transfer risks from issuers to capital market investors. According to (J. D. Cummins 2008), the aim of issuers to issue the CAT bond is to raise funds that will be available to reimburse any potential losses from catastrophic events. The author (ibid.) also states that, as a high-yield bond, CAT bond investors may gain a high return if no catastrophic events occur during the period to bond maturity. However, investors are likely to be exposed to higher risk because the CAT bond has received a lower BB level rating from rating agents, known as a 'junk bond'. Therefore, CAT bond investors could lose partial or full investment in the event of an unexpected catastrophe.

For example, let us assume that the capital of a three-year catastrophe bond contract is £1000, and the annual coupon rate is 8% with a quarterly payment. To define the payoff of the catastrophe bond, one needs to pre-define and measure trigger events, such as natural disasters and man-made disasters. The cash flow of returns and losses for a CAT bond investor can be calculated in the following three scenarios.

a. No catastrophic event occurs.

Time (months)	0	3	6	9	12	15	18	21	24	27	30	33	36
Cash flow	-1000	20	20	20	20	20	20	20	20	20	20	20	1020

Investors will pay £1000 at the beginning of the purchase and receive a 2% quarterly coupon payment every 3 months. At the maturity of the CAT bond, investors receive the original principal of £1000 plus 12 times coupon payment of £20. In this case, the total return for the investor is £1240 with a net profit of £240.

b. A catastrophic event occurs with no protection to the principal.

If a catastrophic event occurs in this scenario investors will lose the principal and the rest of the coupon payment from the day of the catastrophic event. For example, if a catastrophic event occurs between months 21 and 24, then the returns and losses for the investor can be calculated as:

Time (months)	0	3	6	9	12	15	18	21	24	27	30	33	36
Cash flow	-1000	20	20	20	20	20	20	20	0	0	0	0	0

Here, investors paid £1000 at the initial period and received only seven instalments of coupon payments prior to the catastrophic event. The return will be 7 times the quarterly coupon payment of £20 with the loss of all principal due to the catastrophic event. The total return is £140, resulting in a net loss of £860 for the investor.

c. A catastrophic event occurs with principal protection.

In some pre-defined bond contracts, investors can request protection from the principal whether there is a catastrophic event or not. In this scenario, the issuer will offer a principal protection scheme, which offers only 30% of the original coupon rate that can be gained, plus the full principal. Therefore, the following investor's cash flow will look like this:

Time (months)	0	3	6	9	12	15	18	21	24	27	30	33	36
Cash flow	-1000	6	6	6	6	6	6	6	6	6	6	6	1006

In this scenario, the investor will receive its original investment of £1000, which ignores the occurrence of catastrophic events. However, the gains from the coupon payment will be reduced accordingly by 30% of the original coupon payment. Therefore, under a catastrophe situation, the net profit of the investor will be 12 times the coupon payment of £6, which is £72. If a catastrophic event occurs between weeks 24 and 27, the net profit will be 8 times the coupon payment of £6, which is £48. With this specific financial product, the CAT bond is a benefit for (re)insurance companies to hedge the potential bankruptcy from catastrophe risks, and investors will receive coupon payments.

To price the bond in the market, researchers have contributed several approaches using different assumptions to forecast and price the dynamic spread of the catastrophe bond (Z. Ma et al. 2017; Shao 2015). The real catastrophe bond pricing model contains several assumptions, the dynamics of interest rate, the stochastic occurrences, and unpredictable severity of catastrophic events, all of which are discussed in the next section. Other factors mentioned by (Braun et al. 2022; Gomez and Carcamo 2014), such as varieties of catastrophic events, the value of insured properties, different regions, and dynamic interest rates are influential in the pricing of the bond.

3.2.1 Model assumptions

There are four commonly used assumptions in the catastrophe bond literature: Firstly, much of the literature assumes that the non-arbitrage market had already existed, such as (Baryshnikov et al. 2001; S. H. Cox and Pedersen 2000; D. Cummins et al. 1999; Lee and Yu 2002). An arbitrage opportunity is that the given purchase price of the bond in one market can be sold immediately in another market with a higher price. The trade in different markets will generate risk free gains with high prices. To avoid this influencing factor in the valuation of a bond, a CAT bond is assumed to be trading in an arbitrage-free investment market. This assumption provides the basis that the CAT bond will be valued in a theoretical market where there is no asymmetric information and no transaction cost. Poncet and Vaugirard (2002) and Vaugirard (2003) then extended the consideration to price insurance-linked securities in an arbitrage market, and Vaugirard developed a simple arbitrage approach to the pricing of CAT bonds.

Secondly, one of the main assumptions is that the occurrence of a catastrophic event in accordance with the Poisson process is a mutually independent occurrence, as discussed in (Christensen and Schmidli 2000; Young 2004). In the probability and statistics field, the Poisson process is a simple and widely used stochastic process for modeling the arrival times of events to a system. Furthermore, *mutually independent* refers to the occurrence of each event as having the same probability but without effects upon other events. In other words, this assumption limits the occurrence of catastrophic events independent of each other, and catastrophe risks are independent of default risk and financial market behaviour. However, Vedenov et al. (2006) hold a different view when considering the occurrence of catastrophic events as a Poisson process because the assumption may only be suitable to price the bond under existing contracts - with no restrictions on purchases and sales at any time. The authors (ibid.) also argue that the assumption is only suitable for events caused by natural catastrophes, but not terrorism events. However, H. Kunreuther (2002) disagrees with the point of view from the above literature and states that the (re)insurance market contains above $10 billion funds up to 2001, but none of these funds have been used to cover terroris evenmts. Kunreuther (2002) therefore proposes a terrorist CAT bond.

Thirdly, the dynamic interest rate process will follow the stochastic process with a Brownian Motion. The Brownian Motion is used, among other things, to describe the random behaviour of fluctuations in asset prices. Defining the dynamic movement of interest rate using Brownian Motion has been used widely in the most famous interest rate models, such as VasicekVasicek (1977) and the Cox-Ingersoll-Ross (CIR) model of J. C. Cox et al. (1985); these models are recognised as the benchmarks of simulation models for dynamic interest rate.

Fourthly, some other assumptions are proposed in the literature. For instance, Zanjani (2002) presents three key assumptions relative to the research of the present thesis: 1.) insurers have a high probability of default because the average loss is unforeseen; 2.) enterprises may not hold liquid capital because it is costly; and 3.) consumers are aware of insolvency.

3.2.2 Valuation framework

According to Brigo and Mercurio (2007), the value of a bond will be priced by considering the bond as a zero-coupon bond and the investor will purchase the bond at the beginning with a high percentage of discount from the face value. The authors (ibid.) state that the zero-coupon-bond price P(t,T) will be equal to the discount factor D(t,T) under the condition of the same amount of investment fund. However, a catastrophe bond valuation will contain additional considerations of the occurrence and severity of catastrophic events. On top of the valuation of zero-coupon bond, the dynamic processes of the expected losses from catastrophic events needs to be computed by predicting the probability of occurrence and severity of future catastrophic events based on historical data. According to Merton (1976), the dynamic occurrence and severity of catastrophic events will lead to an unanticipated price during the valuation of a CAT bond; therefore, in the present thesis a Martingale measure assumption will be applied to ensure that the real probability measurement is equal to the risk-neutral measurement. A Martingale measure is denoted by Q and the expectation of this Martingale measure is equal to the actual probability measure, P, where $E^Q[X] = E^P[X]$, (See: (S. H. Cox and Pedersen 2000; Nowak and Romaniuk 2013; Shao et al. 2017). Based on the assumption that a CAT bond will be priced in an arbitrage-free market at any time, the value of the contingent claim can be calculated to represent the uncertain outcome from the combination of unpredictable probability of occurrence and severity of catastrophic events. The value of a catastrophe bond can thus be expressed as:

$$V_t = E_t^Q \left(exp\left(- \int_t^T r_s \, ds \right) C_T \right), \tag{3.1}$$

where

E_t^Q represents the expectation of risk-neutral measure;

V_t is the value of the present value of the future contingent claim C_t (known as the zero-coupon CAT bond value);

r_s is the interest rate and $exp\left(- \int_t^T r_s \, ds \right)$ is a stochastic discount factor.

From Eq. (3.1), one can observe that two variables require definition: the dynamic interest process and the contingent claim. The interest rates have been divided into short-term and long-term. According to the OECD definition (OECD-Data 2022b), short-term interest rates are normally measured as a percentage of the average daily rate and are based on 3-month money market rates, such as the Treasury Securities Rate. Short-term interest rates represent the rate of short-term debt for financial institutions, governments, or corporations that will be affected in the market. Also, (OECD-Data 2022a) shows that long-term interest rates are commonly measured as a percentage of the average daily rate, but it refers to the rate of 10-year-maturity government bonds, which is related to risk level of borrowers, price set by the lender, and change of capital value. Long-term interest rates are indicated by the traded value of the government bonds, not the initial issuance interest rate. Long-term interest rates are also one of the most significant indicators for businesses to make investment decisions where, e.g., businesses should accept an investment in new equipment with low long-term interest rates and reject the high long-term interest rate investments. Essentially, the price of a bond calculated by using the London Inter-Bank Offered Rate (LIBOR) is recognised as a risk-free bond. The fluctuation of interest rate should be modeled as the most significant influence in the decision-making for asset valuation in the financial market. In the insurance field, the dynamic interest rate will be modelled as a diffusion process with constant parameters; therefore, whether or not the model reflects the real interest rate is one of the top issues needing to be considered (Siu 2010). Zeytun and Gupta (2007) comment that the fluctuation in the independent interest rate model is simply not observed as strongly as in practice. Therefore, this thesis will review and examine two one-factor models in order to measure the movement of interest rates: (1) the Vasicek model, and (2) Cox-Ingersoll-Ross (CIR) model.

According to Mamon (2004), the classic Vasicek model is one of the most efficient models for pricing fixed-income derivatives. As a one-factor model, Vasicek (1977) assumes that the interest rate will be moved by only a single source of market risk, which is represented by a stochastic differential formula:

$$dr_t = k(\theta - r_t)dt + \sigma dW_t, \tag{3.2}$$

where

r_t is the dynamic interest rate at time t;

W_t is a Wiener process (Brownian Motion), which is indicating the fluctuation of interest rates follow the real-valued continuous-time stochastic process;

k, θ, σ are all positive constant, where $k(\theta - r_t)$ is the drift factor, k is the speed of reverting to the average rate θ, and σ is volatility.

As shown in Zeytun and Gupta (2007), the main feature of the Vasicek model is that the interest rate will return to the mean level θ by speed k over time. The parameter k in the function will pull down/up the interest rate r when it is greater/less than the average rate θ. A negative k will lead to a negative drift, thereby reducing the rate to approach the mean interest rate θ, and vice versa. As one of the earliest stochastic models, mean reverting and tractability in the measurement are the most significant features in the Vasicek model. However, that the interest rate may become negative remains a drawback of the Vasicek model. A number of alternative mathematical models rooted in the Vasicek model have addressed the model's shortcomings. For instance, as an extension of Vasicek, the classic Cox-Ingersoll-Ross (CIR) model imposes a condition $2k\theta \geq \sigma^2$ to keep the interest rate always greater than 0.

First presented in 1985, The Cox-Ingersoll-Ross (CIR) model has become the benchmark simulation model for dynamic interest rate, especially in the fixed-income securities field for the valuation of analytical bonds and bond options (See: (Lee and Yu 2002; Nowak and

Romaniuk 2013; Vaugirard 2003). The model assumes that the risk-neutral measure (Q) is equal to the practical measure (P); therefore, under the risk-neutral measure (Q), the dynamic interest rate is expressed as:

$$dr_t = k(\theta - r_t)dt + \sigma\sqrt{r_t}dW_t, \tag{3.3}$$

where

r_t is dynamic interest rate;

W_t is a Wiener process;

k, θ, σ are all positive constant.

In the real world, the practical measure (Q) for the dynamic interest rate needs to consider the additional risk to each factor and the dynamic movement of the interest rate. Under the practical measure (P), the interest rate process is thus expressed as:

$$dr_t = k^*(\theta^* - r_t)dt + \sigma\sqrt{r_t}dW_t^* \tag{3.4}$$

where

$k^*, \theta^*\ and\ W_t^*$ is the factor that considers the influence of risk in the real world.

As shown in Lee and Yu (2002), $k^* = k + \lambda_r$; $\theta^* = \frac{k\theta}{k+\lambda_r}$ and $W_t^* = W_t + \int_0^t \frac{\lambda_r\sqrt{r(s)}}{\sigma}ds$. λ_r denotes the market value of risk and W_t^* is a Brownian Motion under the consideration of influence with the risk under the practical measure (P).

With regard to Eq. (3.4), the dynamic interest rate under the practical measure, P, is expressed as:

$$dr_t = [k\theta - (k + \lambda_r)r_t]dt + \sigma\sqrt{r_t}d(W_t + \int_0^t \frac{\lambda_r\sqrt{r(s)}}{\sigma}ds) \tag{3.5}$$

To calculate the market value of risk (λ_r), we apply the Radon-Nikodym theorem by comparing the practical measure (P) and risk-neutral measure (Q). The function of Radon-Nikodym derivative is denoted by $\frac{dv}{d\mu}$, where $v\ and\ \mu$ represent any measure, such as the P and Q measures. Under the condition that the expectation of risk-neutral measure (Q) is absolutely continuous to the practical probability measure (P), the function is satisfying $E^Q[X] = 0,\ E^P[X] = 0$. Hence, the comparison of the two measures can be expressed as:

$$\frac{dQ}{dP}| = \exp\left(-\frac{1}{2}\int_0^t \frac{\lambda_r^2 r_s}{\sigma^2} ds + \int_0^t \frac{\lambda_r \sqrt{r_s}}{\sigma} dW_t^*\right) \tag{3.6}$$

By applying the Radon-Nikodym derivative model under the assumption of $E^Q[X] = E^P[X]$, the change of risk-natural measure Q for practical probability measure P is a stochastic process represented by $\lambda_r^*(t)$, (Z.-G. Ma and Ma 2013; Shao et al. 2017), where the change process of risk $\lambda_r^*(t)$ can be calculated by following:

$$\lambda_r^*(t) = \frac{\lambda_r}{\sigma}\sqrt{r(t)}, \qquad t \in [0, T] \tag{3.7}$$

In the CIR model, the drift factor $k(\theta - r_t)$ is similar to the Vasicek model, where k is the speed of reverting to the average rate θ; σ is volatility and k, θ, σ are all positive constant. According to J. C. Cox et al. (1985), the CIR model needs to satisfy the condition of $2k\theta \geq \sigma^2$; the purpose of imposing this setting is to keep the figure r_t within the positive domain. The setting of the term $\sqrt{r_t}$ eliminates the main shortfall of a possible generation of negative interest rate from the Vasicek model. By using this setting, volatility term $\sigma\sqrt{r_t}$ will stop the Wiener process randomness when the interest rate figure approaches 0, which avoids negative interest rates. Therefore, the CIR interest rate model is becoming a benchmark model in the literature for simulating the fluctuation of the interest rate process.

As shown in Eq. (3.1), the contingent claim is another variable needing to be defined; it contains two dynamic processes: the occurrence (frequency), and the severity of the catastrophic events. As in Burnecki et al. (2011), the dynamic processes of occurrence and severity compose the contingent claim, which is calculated as the dynamic losses process in the typical insurance risk model. Most insurance businesses are exposed to systematic and non-systematic risks; however, this differs from catastrophe insurance coverage that depends solely on the occurrence of catastrophic events (Christofides 2004). Therefore, the two main components in a catastrophe bond contingent claim are the counting process of events (occurrence), $[N_t]$, where $t \geq 0$, and total claim size (severity) $[X_j]$, where $j = 1$. As stated in Aase (1999) and Z.-G. Ma and Ma (2013), the contingent claim will be assumed as the aggregate losses following the compound Poisson process. The *compound* Poisson process is a significant stochastic process which defines that the occurrence (N_t) follows the Poisson process; and the severity (X_j) is a random process with a specified probability distribution. The contingent claims in period, *t*, is considered as:

$$L_T = \sum_{t_j<\tau} X_j = \sum_{j=1}^{N_t} X_j, \qquad (3.8)$$

where

L_T is contingent claims, $L_T = 0$ when $N_t = 0$;

N_t is number of occurrences that follow Poisson process at time, *t*, $(t \in [0, T])$;

X_j is claim size of the jth event, which is independent from N_t.

As shown in Eq. (3.8), the number of occurrences is assumed to follow the Poisson process. A Poisson process, a discrete probability distribution used to describe the probability of a given number of catastrophic events occurring in a fixed period, is denoted as:

$$\mathrm{P}(N_t) = e^{-\lambda(\mathrm{t})} \frac{[\lambda(\mathrm{t})]^k}{k!} \qquad (3.9)$$

where

N_t is the counting process with the intensity parameter λ, where $\mathrm{t} > 0$ and $\lambda > 0$;

k is the number of occurrences of catastrophic events, where k = 0, 1, 2…

3.2.3 CAT bond pricing model specification

The analysis next sets out the process of the catastrophe bond valuation model with the payoff function. By design, the catastrophe bond is a zero-coupon bond and sells with a deep discount on its face value to investors. The payoff function is:

$$P_{CAT} = \begin{cases} \rho F & if\ L_T > D \quad (bond\ is\ triggered), \\ F & if\ L_T \leq D \quad (otherwise), \end{cases} \qquad (3.10)$$

where

P_{CAT} is payoff of catastrophe bond;

ρ is proportion of the face value repaid to investors;

F is face value of CAT bond;

L_T represents aggregate losses at maturity date T;

D is trigger value.

When aggregate losses (L_T) are greater than the trigger value, an insurance company will cover any losses occurring from the event; however, a less than trigger loss may not receive any reimbursement from an insurance company. To summarise, according to Eq. (3.1), the value of a zero-coupon CAT bond at maturity, *T*, under the risk-neutralised pricing measure Q is given by:

$$V_t = E^Q\left(e^{-\int_t^T r_s ds} P_{CAT}(T)|F_t\right) \qquad (3.11)$$

$$= E^Q\left(e^{-\int_t^T r_s ds}|F_t\right) \bullet E^Q(P_{CAT}(T)|F_t)$$

where

V_t is the value of a zero-coupon CAT bond;

E^Q is the expected risk-neutral measure.

According to Brigo and Mercurio (2007), the expectation of a risk-neutral pricing measure is equal to the price of a zero-coupon bond $B_{CIR}(t,T)$ thus:

$$E^Q\left(e^{-\int_t^T r_s ds}|F_t\right) = B_{CIR}(t,T)$$

When we substitute the term zero-coupon bond and replace the payoff function in (3.10), the value of a CAT bond is:

$$\begin{aligned} V_t &= B_{CIR}(t,T) \bullet E^Q(P_{CAT}(T)|F_t) \\ &= B_{CIR}(t,T) \bullet (F\rho P\{L_T > D\} + FP\{L_T \le D\}) \\ &= B_{CIR}(t,T) \bullet F[\rho(1 - P\{L_T \le D\}) + P\{L_T \le D\}] \end{aligned}$$

In this way, a zero-coupon CAT bond can be priced through the following equation:

$$P_{CAT} = B_{CIR}(t,T) \bullet F \bullet \left[\rho + (1-\rho) \bullet \sum_{j=1}^{N_t} X_j\right] \qquad (3.12)$$

3.3 Resilience bond valuation

The resilience bond is a relatively newly published bond having a similar design to a catastrophe bond; as such, it is a loan given to the issuer by investors who are expecting to receive a fixed interest return. According to Re:Focus (2015), a resilience bond has three main functions: insurance, rebate and resilient project. The insurance function of the resilience bond is, accordingly, designed like the conventional CAT bond, but the distinguishing features of resilience bond has led to a different consideration to the catastrophe bond valuation method. To price a resilience bond, the valuation method needs to calculate the impact of resilient infrastructure which creates portion of the insurance value from the mitigation of risks. The reduced risk from the project will be quantified into a rebate and invested back into the project. Therefore, the pricing model of resilience bond will consider an impact factor, which calculates the percentage reduced to the historical losses data by having the resilient project.

3.3.1 Resilience bond pricing model specification

Resilience is defined as the ability to resist and recover from unexpected catastrophic events. However, Murray-Tuite (2008) state that the term resilience has not been strictly defined or measured, therefore, the measurement of effectiveness between do-something to do-nothing to improve the resilience may define the impact. (Re:Focus 2015) assert that no unified model for resilience bond exists since each bond is tailored to type of resilient project, local market, and insurance policy. Accordingly, this thesis proposes an impact parameter (ǯ) to indicate the impact of with/without the resilient project to the whole system. Hence, the impact factor can be calculated as:

$$\text{Impact}(\text{ǯ}) = \frac{(\text{Cost}_{no-resilient\,project} - \text{Cost}_{Resilient\,project})}{\text{Cost}_{no-resilient\,project}} \qquad (3.13)$$

where

$\text{Cost}_{Resilient\,project}$ is the cost with a resilient project;

$\text{Cost}_{non-resilient\,project}$ is the cost without a resilient project.

With the expectation that the resilient project will improve the resilience level of the whole system and reduce unexpected catastrophe losses, by re-shaping the catastrophe bond payoff function, the resilience bond payoff function under the consideration of the impact factor in Eq. (3.13) is computed as follows:

$$P_{RB} = \begin{cases} F\rho \quad if\ L - ǯ\mathrm{L} > D \quad \left(bond\ is\ triggered\right), \\ F \qquad if\ L - ǯL \leq D \quad (otherwise), \end{cases} \tag{3.14}$$

where

P_{RB} – is payoff amount at maturity;

ρ – represents the proportion of the face value repaid to investors;

F – is face value of the resilience bond;

L – is aggregate losses;

D – represents trigger value;

ǯ – is the impact of the resilient project, where $0 < ǯ < 1$.

In sum, according to Eq. (3.1), the prices of the zero-coupon resilience bond at maturity T under the risk-neutralised pricing measure Q, is given by

$$V_t = E^Q\left(e^{-\int_t^T r_s ds} P_{RB}(T)\right) = E^Q\left(e^{-\int_t^T r_s ds}\right) \bullet E^Q(P_{RB}(T))$$

The expectation of risk-neutral pricing measure is equal to the price of a pure-discount bond

$$E^Q\left(e^{-\int_t^T r_s ds}\right) = B_{CIR}(t,T)$$

Then,

$$V_t = E^Q\left(e^{-\int_t^T r_s ds} P_{RB}(T)\right) = B_{CIR}(t,T) \bullet F \bullet (E_t^P[C_T])$$

$$= B_{CIR}(t,T) \bullet (\rho \bullet F \bullet P\{L - ǯ\mathrm{L} > D\} + F \bullet P\{L - ǯL \leq D\})$$

$$= B_{CIR}(t,T) \bullet F \bullet [\rho \bullet (1 - P\{L - ǯL \leq D\}) + P\{L - ǯL \leq D\}]$$

Therefore, the final resilience bond pricing model becomes

$$B_{CIR}(t,T) \bullet F \bullet \left[\rho + (1-\rho) \bullet F_l\left(T, (L - ǯL \leq D)\right)\right], \tag{3.15}$$

where

ρ – is the proportion of the face value repaid to investors;

F – is face value of resilience bond;

$B_{CIR}(t,T)$ – is the dynamic interest rate by using the CIR model;

$F_l\left(T, (L - ǯL \leq D)\right)$ is the distribution of the losses less than or equal to threshold D.

After having built on the pricing model of resilience bond, the next step in this thesis is to explore the design and structure of the resilience bond. Since the concept of resilience bond is different from catastrophe bond, the terms relating to the resilience bond need to be clarified.

Resilience bond maturity

The resilience bond maturity period will coincide with the project period and so will be divided into different phases. The first maturity period of the bond could be 1- to 3-years, depending on the first construction phase. Thereafter, the bond can continue to have a second or third maturity period to follow the construction phases, with annual maturity at the operation phase. For example, Inderst (2009) shows that the start-up phase for an infrastructure-related project can be financed from the primary market, then the secondary market will relate to the operation of the infrastructure asset.

Triggers

There are several types of triggers can be used to measure the different thresholds. When resilience bond reaches the requirements to make reimbursement, such as parametric, indemnity, and modelled loss triggers.

- Indemnity - are the actual losses from catastrophic events.
- Parametric loss - a physical measure of the event such as magnitude, wind speed, and location. The aggregate losses in the industry will be estimated by an independent party, such as Property Claim Services (PCS)
- Modelled loss - triggers are set by mathematical calculations.

A trigger for the insurance-linked securities is the actual losses incurred by the catastrophic events that reach the reimbursement threshold. Triggers can be pre-specified in the contract by promoters and insurance companies because different triggers are likely to lead to different effects. Trigger thresholds are set based on the Swiss Solvency Test (SST) ratio, which is less than 135% of the SST ratio (SwissRe 2013).

Table 3-1 Pros and cons of triggers

Triggers	Advantages	Disadvantages
Parametric: a repayment triggered by the actual losses of, or damage to a physical asset.	1. High data transparency 2. Low moral hazard 3. Short claim period 4. Can be adopted in developing economies with low qualitative data and insurance penetration.	1. Basis risk is higher than other triggers 2. Reimbursement may differ from the actual damage losses.
Indemnity: a pre-defined threshold in the contract by specifying the level of losses.	1. Reimbursement is similar to sponsor's actual damage cost.	1. Costly and complicated to recognise risk exposure of the sponsor's insurance stock. 2. Long claim settlement period 3. May contain moral hazard
Index: an index trigger is the modeled losses.	1. Symmetric information between investors and sponsor 2. High data transparency 3. Low moral hazard 4. Lower basis risk than parametric trigger	1. High basis risk to the sponsor 2. Actual cost may be different for reimbursement from CAT bond 3. Risk increase for larger geographical areas
Hybrid	A combination of all triggers	A combination of all triggers

Source: ENTROPICS Asset Management AB.

The modelled loss will be selected as the trigger in this research since the modelled loss may directly show the difference between prices based on various level of triggers.

Financial structuring

According to Blue-forest-conservation (2017), the issuance of a resilience bond contains an opportunity to promote a public-private partnership between private investors and public institutions. It provides the chance to enable private capital to finance the resilience infrastructure projects. The bond will provide diversification of cash flow for catastrophe recovery and offer investment funds to the resilient infrastructure project. The upfront cost for resilient infrastructure project will be shared by all beneficiaries in different proportions at the project planning stage, then the cost will be covered by the investor's capital after the bond is sold to investors.

Issuance

Resilience bonds can be designed into different tranches. The first tranche main issued for the construction period, then, the second tranche can be issued for the middle construction phase and the third tranche can be issued for the operation phase. For example, as in the design of USAA Hurricane Bonds (S. H. Cox and Pedersen 2000), the first tranche of the bond principal is guaranteed and only the coupons are exposed to hurricane risks, where the coupon rate is the London Interbank Offered Rate (LIBOR) plus 2.73%. In the second tranche, both the bond principal and coupon will be exposed to hurricane risk, where the coupon rate is the LIBOR plus 5.76%. However, as LIBOR is ceased, then replacement basic rate of interest could be considered, e.g., US T-bill. If set the resilience bond in short-term by several phases, the bond will be facing a market risk that investors will predict the risk reductions and benefits from the project from partial phases of it, which will affect the price by undervaluing the whole resilience project. If set the resilience bond in long-term to accord with the construction period of the resilience project, the bond will be facing several market risks, such as the benefits from the project and the rebate investment to the project will decrease along with the drop in the price for the specific level of risk in the capital market. On the contrary, if the price for the specific level of risk increases in the capital market, it will lead to a rise in the insurance cost and higher program expenditure(s).
a. events must be pre-specified in the insurance contract. For instance, earthquakes and floods.
b. Sponsors must pre-specify the type of damage and exposure, for example, supply chains, business operations, and physical assets.
c. Sponsors must pre-specify the severity of an event, such as wind speed and earthquake level.

3.4 Summary

This chapter has studied the catastrophe bond valuation method and model as the foundation for building the pricing model for a resilience bond. Based on the catastrophe bond pricing model, the analysis has discussed the framework of the assumptions used to support the valuation model and analysed the main method for simulating the dynamic interest rate and contingent claim. To price the resilience bond, the model should consider a new parameter, the impact factor (ǯ), which represents the subtraction of risks by developing resilient infrastructure projects. Since a resilient infrastructure project has been assumed to reduce the risk of failure of the whole infrastructure system to the future catastrophes, one needs first to quantify the mitigated risks generated from the resilient infrastructure projects to the whole system, which is the difference between the original status of the infrastructure and after mitigation of risks status. The change of the risks will be quantified into percentages that stand as the impact factor of the resilient infrastructure project on the whole infrastructure system.

The resilience bond is project-based, where the prices may be highly interdependent concerning the resilient infrastructure project. Therefore, the next focus is on the application of resilience bonds in different fields, such as supply chain disruption resilient infrastructure projects, flood defense resilient infrastructure projects, and building retrofit in Istanbul. To quantify the resilience of the project within the whole system, the study will introduce a new parameter into the original catastrophe bond pricing model to define the new resilience bond pricing model. Impact factor (ǯ) will be used to represent the percentage reduction from the mitigation of catastrophic risks from the resilient infrastructure project.

The model of resilience bond may exist some uncertainties due to imperfections and idealisations. For example, in the assumptions of the model, the condition is the market has no arbitrage opportunity and the expectation measurement Q is equal to the practical measurement P. Under these conditions, the price simulated from the model may not match the practical prices. Besides, the choice of the probability distribution may not exactly match the real dataset, therefore, it will lead to some uncertainty to the final prices. Therefore, the modelled prices may only use as the guidance to discuss about the trend of the price movement and the range of the price at the initial issuing period. The following case studies are focused on different resilient infrastructure projects and the prices of the issuance of resilience bond. Under the consideration of previous mentioned uncertainty, the prices may only suitable for the projects with the assumptions as the guidance of issuance price.

Chapter 4 Financing Supply Chain Resilience Via Resilience Bond: A Case Study of China's Supply Network

4.1 Introduction

Nowadays modern society relies heavily on both physical and social infrastructure networks. The system of infrastructure forms the backbone of any economy (Bektas and Crainic (2007). Meanwhile, infrastructure systems around the world are increasingly being challenged by the dynamic environment (Hao et al. 2015). According to Guha-Sapir et al. (2004), catastrophes have resulted in a severe setback to the development of many countries within the last 30 years by causing 2 million deaths, 182 million homeless people, and nearly $1.4 trillion worth of losses. Therefore, the study of resilience or risk reduction is of utmost significance. Supply chain systems have played an essential role in today's highly competitive business environment since every industry requires support from operation chains behind the business. As modern supply chains grow larger and more complex, the network may become more susceptible to catastrophic events (Schmitt and Singh 2009). According to a survey by ZURICH (2016), approximately 43% of businesses have between 20 to 100 key suppliers; hence, even a small or an indirect disruption will influence the business. For instance, Chrysler immediately changed to road transport instead of air freight for essential components from Virginia to Mexico after the 911 terrorist attack (Erlinghagen and Markard 2012). The Philips semiconductor plant in New Mexico had to be shut down for six weeks in 2000 due to a fire caused by lightning strike; the shutdown led to a supply shortage of components for Ericsson and Nokia (Tomlin 2006). Catastrophic disruptions such as operational errors, shortages of goods, and natural or man-made disasters may lead to unpredictable financial losses. Disruptions and calamities may sever supply chain transportation links that need to be rerouted immediately, but which nevertheless also impose immediate negative impacts onto businesses (Ishfaq 2012). Moreover, in hindsight, the risks from catastrophic disruptions are often broader than forecasting can predict. Higher costs and poor services will occur if a logistics operation is unprepared for contingent disruptions (Barad and Sapir 2003).

To reduce the unforeseen economic losses, improving the resilience of the infrastructure system becomes the priority issue needing to be solved rather than dealing with unstoppable catastrophes. Berkeley and Wallace (2010) argue that a resilient infrastructure should have the ability to decrease the magnitude of and/or save recovery time due to catastrophic events. Furthermore, a resilient system should continue to deliver its core functions despite influential internal or external risks (World-Economic-Forum 2011). Therefore, building a resilient supply chain efficiently and economically has been a key aim for many suppliers and customers, since it will offer fast responses to unexpected losses and allow businesses to bounce back quickly (T. Wu et al. 2007). An effective enhancing project will create more resilience to supply chain networks in the wake of catastrophes.

The present study focuses on the logistics strategy of applying intermodal transport to improve the resilience of supply chain networks. The most global rationale of intermodal transport from the European Conference of Ministers of Transport (ECMT) is to transfer goods by at least two transport modes for logistics freight transportation with the same loading unit (Arnold et al. 2004). According to Rice and Caniato (2003), necessary investment in infrastructure projects and resources is one of the efficient approaches to create resilience, especially in supply chain networks. However, in the general development of infrastructure systems, most nations rely on government support (Gichoya 2005). But public resources contain high opportunity costs; therefore, researchers are noticing that to bring infrastructure finance issues to the capital market is, at present, probably the most dynamic means of innovation. For example, in 2016, UK government infrastructure investment amounted to £18.9 billion, of which £10.3 billion of the funds derived from market sector investment.

Bonds have the potential to move the finance fulcrum away from traditional public-only investment to public-private partnerships. As shown by Orr and Kennedy (2008), private investors have played an essential role in investment for infrastructure-related projects. If bonds can be applied to bring together the public and private sector to create a new flow for infrastructure finance, then the new financing model may also be replicated to reinforce supply chain networks against catastrophes. The resilience bond, as proposed in 2015 by Re:Focus in collaboration with Goldman Sachs, Risk Management Solutions, and Swiss Re, is specially designed to generate rebates for eligible resilient projects. When a supply chain catastrophe-resistant project is complete, payments to the bond investors will drop to reflect the lower risk of the supply chain system. Companies will continue paying the previous higher rate, and the difference will go to paying off the resilient project. Throughout this thesis, the application of resilience bonds in supply chain resilient projects will be introduced as an alternative tool to provide and generate insurance service and generates funds to support an intermodal transportation port (ITP) project, thus enabling supply chains to become more disruption resistant.

4.2 Background

The supply chain allows entities to share logistics activities with different partners around the world. In recent years, global market competition between enterprises has gradually shifted to competition between supply chains, since every industry requires support from operation chains behind the business. Christopher (2016) state that supply chain networking is a business integration that will add value to raw materials and transfer them to end-users. It secures the supply and demand and helps businesses be more competitive in the market. Christopher and Peck (2004) describe how organisations within the same supply chain have become highly interdependent with each other in order to control, manage, and improve the flow of materials and information. However, supply chain management has also become increasingly vulnerable (Jayaram et al. 2000; Warren and Hutchinson 2000). Zsidisin et al. (2005) show that, as the modern supply chain has become more and more complex, many enterprises are now more aware of unforeseen disruptions, which although they have a low probability of occurring, when they do occur, they will bring significant impacts to the supply chain and affect customer demand. Enterprises on the supply chain comprise a complex network and are increasingly likely to experience continual turbulence and unpredictable disruption, because even a small disruption leads to ripple effects across the whole system (Peck 2005; T. J. Pettit et al. 2010). For example, Apple's supply chain spans across several countries and international waterways. Resources for their products come from the U.S., China, Europe, and other Asian countries; they will be assembled in China, transferred to warehouses via logistics services, then distributed globally via various methods. Hence the vulnerable global structure is sensitive to ripple effects from disruptions due to the interdependency of each partner on the same supply chain (Ponomarov and Holcomb 2009). Catastrophe disruptions such as manufacturing interruptions, lack of suppliers, natural catastrophes, or unwilful attacks may lead to huge financial losses. As a low probability and high consequence event, the catastrophe imposes many vulnerabilities onto supply chains resulting in heavy losses (Glenn Richey Jr et al. 2009). Disruptions will also lead to adverse effects on supply chain revenues and costs (Ponomarov and Holcomb 2009).

4.2.1 The role of intermodal transportation port (ITP)

In global supply chains a port is an essential node connecting different entities and supporting the improvement of business integration and goods value addition. However, S. J. Pettit and Beresford (2009) show that the early port logistics in the UK was formed to connect the railway network and the early role of a port was focused on the transport of goods rather than adding value to the goods. The development of ports has since been divided into three generations: the first generation of ports was built to assist navigation, handling and storing of cargo. Activities in the second generation of ports expanded to involve packaging, product labelling, and physical distributions. The third generation of ports enlarged activities to include logistics and distribution services. Along with the expansion of global trade, traditional logistics transportation is no longer a fit-for-all approach to transfer goods between different entities on the supply chain. Road-based freight transport is the major mode for goods movement between cities, but issues such as congestion, vulnerable infrastructure, environmental pollution, and energy loss are increasing due to the overuse of the road networks (Yamada et al. 2009). As a consequence, different transport networks have combined to alleviate externalities. Since then, ports have been developed more efficiently and effectively to connect with surrounding neighbour entities (United-Nations 2002). According to SteadieSeifi et al. (2014), several terminologies of logistics network appear regularly in the literature: multimodal transportation, intermodal transportation, co-modal transportation, and synchromodal transportation.

- **Multimodal transportation**

Multimodal transportation combines at least two types of transportation modes for facilitating the movement of goods, e.g., railway-waterway, roadway-railway, and roadway-waterway. As the modern transport system expands, more impacts on environments are being recorded (Rondinelli and Berry 2000). Therefore, the development of multimodal transportation generally provides the efficient combination of transport and may reduce both the cost and the environmental impacts of transportation. Multimodal transportation can also achieve economies of scale in the business.

- **Intermodal transportation**

Intermodal networks consist of multimodal services and terminals. Intermodal transportation is a particular type of multimodal transportation having at least two modes of transport. A unique characteristic of intermodal transportation is its movement of raw materials and finished products using standard containers without transferring the goods themselves (Y. M. Bontekoning et al. 2004). Intermodal alternatives have been used around the world to save time and costs for goods transportation, especially in Canada, where a network is formed by connecting five major Canadian cities with three major Mexican cities (Ayar and Yaman 2012).

- **Co-modal transportation**

Co-modal transportation is the choice between two or more modes of transportation used efficiently to reach the maximum benefit of each mode. Thus, as the overall journey becomes more sustainable, so does the network. As proved by Dotoli et al. (2013), sustainable transportation can be realised through the use of multimodal and co-modal transportation.

- **Synchromodal transportation**

Synchromodal transportation is defined as a type of multimodal transportation that focuses on the parallel use of available transport modes or specific transport modes based on the timely decisions of transport providers. It seeks the best possible combination to satisfy the planning process from every transport order (Mes and Iacob 2016).

In a supply chain, shippers will generate demand for goods transportation, and carriers will achieve an optimal strategy in the goods movement by using intermodal transportation. Therefore, building onto or upgrading an existing port to be an intermodal port as a connection node in the supply chain is key to reaching optimality because it provides flexibility in the carrier interchange and efficiency to the stops of port selection. For instance, a loaded standard container from the shipper will be transferred via road to the intermodal port; the standard container will then be handled and delivered to customers via rail transportation. As global trade grown, the performance of intermodal transportation networks has become more efficient. The value of multimodal shipments has doubled from 1993 to 2003, including packaging, postal service, road, rail, and water transport. The strategies of logistics networks are changing due to growing demand by customers who require the delivery of a speed-to-market good. Moreover, supply chain internationalisation calls for transport services to optimise their planning procedures (Crainic and Kim 2007). Intermodal transportation ports provide efficient and effective performance in loading, unloading and transfer operations. It has enhanced productivity and competition for the supply chain by reducing time and costs for goods movement. The standard unit, with its seamless cargo movement, is expected to be a highly profitable transfer method due to increased market competitiveness (Loh and Thai 2012). However, an intermodal transport supply chain network has a significant drawback when a catastrophic event happens; with so many interdependent transport services, it would be difficult to coordinate and arrange and bounce back in the face of a catastrophe-caused disconnection.

4.2.2 Disruption in supply chains: The need for resilience

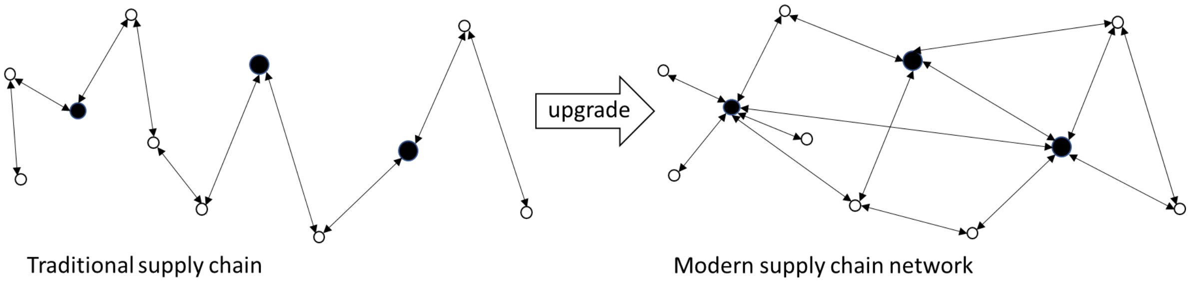
As complexity and distance increase within the supply chain, so does the uncertainty level with regard to the intermodal transportation supply chain network. A disruption to the intermodal port can interrupt the whole supply chain system and lead to an attenuation of competition in business by delaying the delivery of goods. In response, PwC (2016) demonstrates that up to 7% premium increase in the price and significant share gains appear when companies add resilience to their supply chain management strategy (LLOYD'S 2019). As a result, many practitioners and researchers have provided different methods to prepare the supply chain to endure catastrophic disruptions. Global (2007) advocates that just-in-time inventory and other lean manufacturing techniques may significantly reduce the supply chain risk. In addition, X. Li and Wang (2015) also show that the most common way for some businesses is to continuously hold buffer stock and keep several alternative suppliers in case one is disrupted by catastrophe losses. Tomlin (2006) disagrees. A continuous inventory storage strategy may be costly, he states, and it will not be the optimal solution to a labour strike. Christopher and Lee (2004) point out that ‘nervousness’ will compel some businesses to face higher costs for over-ordering with alternative suppliers and squirreling of inventories. Y. Li et al. (2016) suggest that signing a penalty contract with suppliers will cover the financial impacts of unpredictable disruptions. However, a penalty contract is ineffective to suppliers if the final demand is unforeseen under sudden catastrophe situations (Frascatore and Mahmoodi 2008) and a penalty contract may also drive the supplier into bankruptcy (Y. Li et al. 2016).

Improving resilience means reducing probabilities and consequences of failures and saving recovery time (Bruneau et al. 2003). Increasing resilience and reducing costs and losses from disruptions affects the whole supply chain system, from suppliers, producers, distributors, and customers. A resilient supply chain should therefore contain two characteristics:

- Resistance capability to reduce the impact from disruption by minimising the time between pre-disruption and post-disruption recovery.
- Recovery capability to provide flexibility for the supply chain system to return to functionality.

Ponomarov and Holcomb (2009) define the essence of a resilient supply chain as having event readiness and the ability to continue transferring goods as planned after a disruption. As the main link to the supply chain, freight transport must have high-quality performance to ensure the efficient movement of products (Crainic 2003). However, according to SteadieSeifi et al. (2014), conventional logistics transportation is no longer a suitable solution for the modern global supply chain. Resilient supply chain infrastructure projects such as infrastructure upgrades and protections are taking place more and more (Re:Focus 2015). Rice and Caniato (2003) argue that investing in infrastructure to improve resiliency in the supply chain creates flexibility across the network. In particular, building an intermodal transportation port (ITP) or upgrading an existing port to an ITP will build resilience and save time and costs across the entire supply chain network (Ishfaq and Sox 2010) and (Ishfaq 2012). The proposed upgrade of the traditional supply chain to a modern supply chain network, as shown in figure 4-1, contains several flexible intermodal transportation ports.

Figure 4-1. Traditional supply chain and intermodal transportation port (ITP) linked supply chain



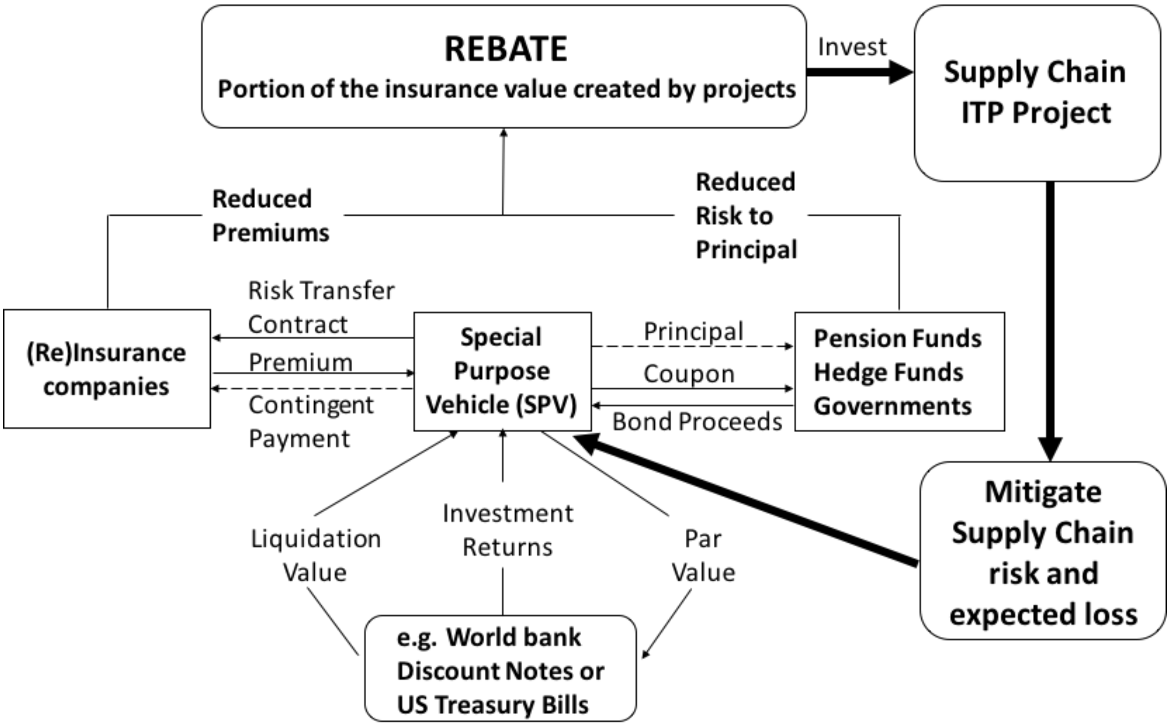
As mentioned earlier, when changing the transport modes, raw materials and finished goods will be transferred to the same unit without handling the materials and goods themselves (SteadieSeifi et al. 2014). According to Y. Bontekoning and Priemus (2004), simulating intermodal transport to accomplish the modal shift is on the agendas of both private and public sector in the transport industry of several governments, mainly in the European Union. Supply chain resilience has gained attention because some infrastructure systems are overexposed and underinsured against unforeseen catastrophe risks. However, investment in a new supply chain infrastructure project requires a large amount of money. Sometimes institutional investors can cover the cost of the project, but some large infrastructure-related projects may need extra investment from private investors.

4.3 Supply chain resilience bond

A resilient supply chain is likely to raise customer confidence as well as reduce the risk of unforeseen losses. An intermodal transportation port project therefore has more advantages, with its constituent flexibility and efficiency in freight shipments, than a traditional logistics transport port. For example, BLG Logistics group in Bremen, Germany is one of the most advanced logistics parks in the world and is ideally linked to European road, rail and waterways (Waters 2003). Freight shipments through the BLG port from countries are transferred using different transport modes with several combinations. It not only provides flexibility to entities, but also brings resilience to the supply chain network. Besides, by applying the intermodal service, the goods are handled by standard containers, thus mitigating the movement time and cost. However, although catastrophic disruptions have a low probability of happening, when they do occur, they significantly break the connection of the supply chain system and bring unpredictable losses for businesses. Consequently, shippers and carriers may prefer to seek financial protection from insurance companies to offset the missing market opportunities. However, in the event of huge catastrophes, the need for insurance companies to bring excess coverage would likely lead to bankruptcy. Instead, resilience bonds could be considered as an effective financial tool for insurance companies to share the risks in the capital market and mitigate the risk of collapse of the supply chain by offering funds for the development of intermodal transportation ports. The resilience bond is a financial tool designed to transfer risks to the capital market and provide both financial coverage and investment for resilient physical infrastructure projects (Vaijhala and Rhodes 2018).

The design of a supply chain resilience bond with an intermodal transport port (ITP) is set out in figure 4-2. The basic insurance function of the resilience bond is in accordance with the catastrophe bond. Sponsors can be (re)insurance companies and the issuer can be a special business entity, also known as a Special Purpose Vehicle (SPV). Investors are normally from the institutional investors. To mitigate the risk of post-disruption financial consequences, entities would seek insurance services from the insurance company. After that, the insurance company would enter into a risk transfer contract with the SPV to issue bonds to reduce the default risks from catastrophe. The SPV issues bonds for insurance companies and sells the bonds to capital market investors to deposit ready-for-reimbursement principal in a collateral account, where the principal will only be invested in the highly-rated market (J. D. Cummins 2008). Moreover, a unique function of the resilience bond is that a third-party evaluator will assess the risk mitigated from an eligible resilient project, then measure and transfer the reduced risks into a deduction of premium and principal in 'rebate' form, which will be invested back into the development of the resilient infrastructure project (Vaijhala and Rhodes 2018).

Figure 4-2 Supply chain resilience bond with intermodal transportation port (ITP) project



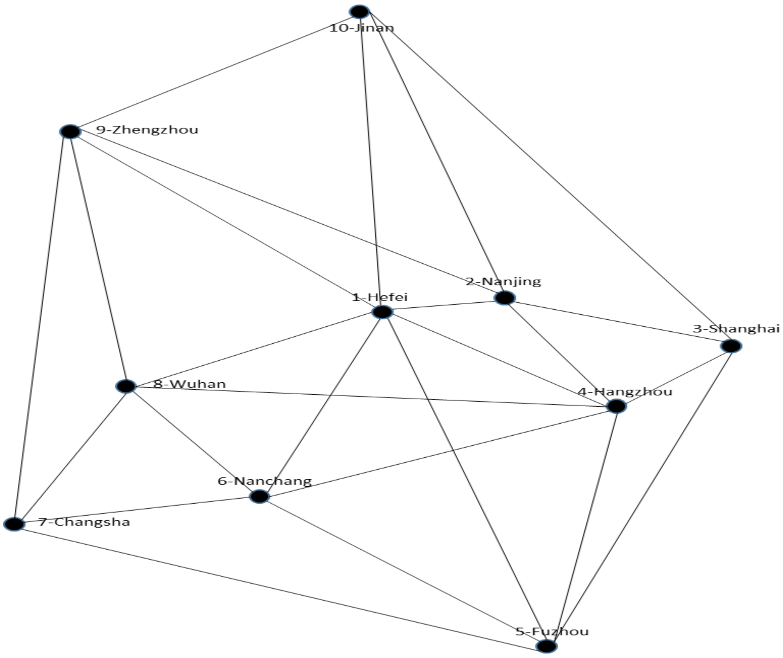
A conventional CAT bond has maturities at 3 or 5 years, and returns will have followed the floating London Interbank Offered Rate (LIBOR) coupon, plus the premium, at a rate between 2% and 20% (Shao et al. 2015). Unlike the CAT bond, the resilience bond is coordinated with project development timelines and milestones (Re:Focus 2015). The threshold for both bonds would be pre-defined in the contract between issuer and sponsor. Although CAT bonds are designed to diminish the issuer's losses from catastrophes, if a catastrophic condition occurs, investors may lose partial or the entire principal (Hagedorn et al. 2009). The design of a resilience bond, however, brings incentives to the infrastructure projects and the 'rebate' is a source of funding used to fund the project itself, which reduces the long-term physical risks for the infrastructure system (Vaijhala and Rhodes (2018). The rebate is generated from the estimation of the reduction of expected losses with a resilient protective infrastructure project. Since the proposed bond is new to the financial market, it is crucial to price the supply chain resilience bond fairly among issuers and investors. With this in mind, the present research next sets up a simulation in order to provide a pricing method.

4.3.1 Pricing model for supply chain resilience bond

To price the resilience bond under the consideration of supply chain intermodal transportation port (ITP) project, one needs to measure the impacts of with- and without- building the ITP project. A resilience bond will only be issued for an eligible project that can be specified to offer potential risk reductions to the whole system. As per Murray-Tuite (2008), resilience can be measured as the comparison between a system with or without a strategy. The value of the resilience bond is largely in the assessment of the percentage of risk and cost mitigated by the eligible project to the whole system. Therefore, resilience in this study is understood as the percentage of recovered performance due to the ITP project -- with respect to the performance without the ITP project. An impact parameter is proposed to represent the change with and without the ITP project. However, the port may perform differently under variable conditions, such as labour efficiency, weather conditions and document processing, among others.

According to Re:Focus (2015), the resilience bond is modeled using two scenarios to estimate the risk reduction: pre-resilient projects and post-resilient projects. In the next section, a simulation test is set up to measure the impact parameter, e.g., to assess the effectiveness measurement of the ITP project to the cost. Figure 4-3 shows the supply chain network in China which assumed the cities as the node for the supply chain network.

Figure 4-3. Supply chain network in China



Impact parameter simulation assumes that 1-tonne of goods will be moved from Changsha (node 7) to Shanghai (node 3) within the supply chain network between several cities in China, comprising 10 node cities and 25 links. The goods will be moved by standard containers. This simulation study follows Ishfaq (2012) in setting the transfer time as 1 hour, and assumes the expenditure of transfer is 200 *yuan*. The simulation will only consider the two transportation modes: Rail and Road. Any node within the route contains two transport modes and an interchange occurring during the goods movement is assumed as a node in the intermodal transportation port (ITP). In our proposed network and its features, the study simulates and tests the supply network with a catastrophic event that disconnects the ITP port. The catastrophic event will lead to an increase in the cost of the goods movement due to delays in transport, damage of goods, or additional costs to change route and transportation mode. The measure of effectiveness is therefore based on the cost mitigated by the tested ITP-node, where the total cost of 1-tonne of goods moved will be shifted from the original node to the destination node with (and without) the target ITP-node. All costs will be computed and compared based on real-time data from the official website. The data include price and distance of every path in the supply chain network indicated by roadway p_{rd}/d_{rd} and railway p_{rl}/d_{rl}. To satisfy the common selection of route, the study assumes that logistics companies will choose the cheapest cost combination of transport modes to move goods. The cheapest cost path of moving 1-tonne of goods using any transport modes will be calculated to fulfil the minimum cost function:

$$\begin{cases} C_{rd} = f(p_{rd}, d_{rd}) \\ C_{rl} = f(p_{rl}, d_{rl}) \\ C_{decision} = \min\,(C_{rd}, C_{rl}), \end{cases} \tag{4.1}$$

where

$C_{decision}$ is the choice to use roadway or railway transport based on cost comparison.

According to Zhang (2012), the shortest path problem can be applied to find a path containing a minimum weight sum between two known nodes; the shortest-path solving method has been used to find the cheapest path for the movement of the goods and the weight in the method can be replaced as distance, flux and cost, and so forth.

The procedures for selecting the cheapest transport mode yields 5 steps: (as in figure flowchart 4-4)

Step 1: Input the price and distance of goods movement for every route using roadway and railway within the supply chain network.

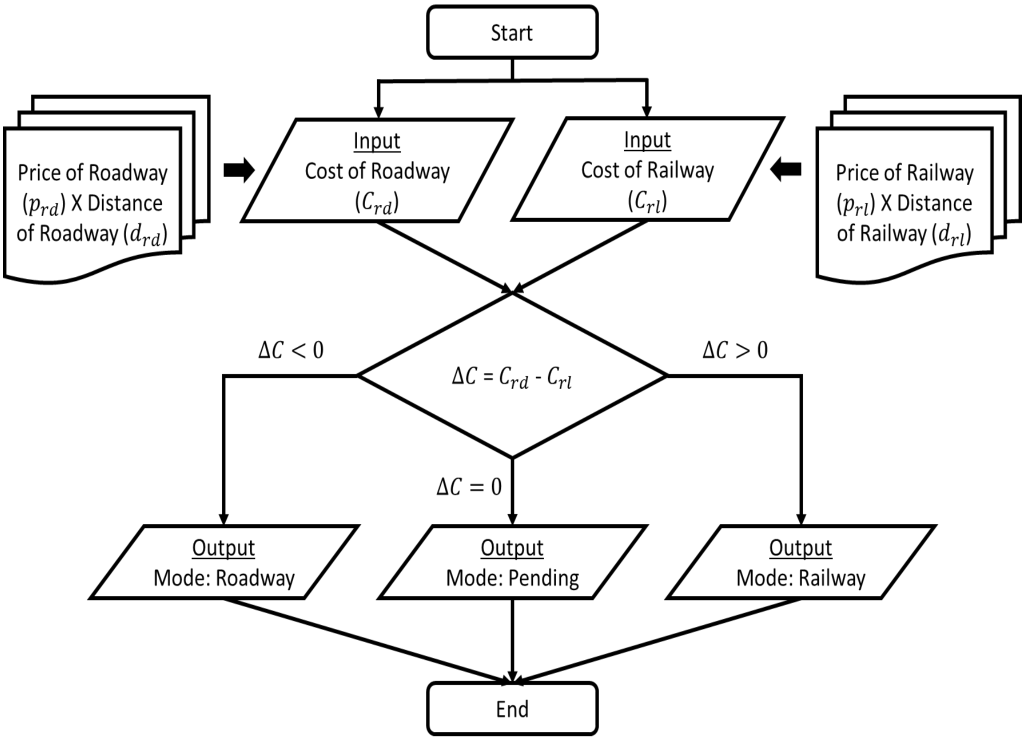
Step 2: Compute the total cost for all paths in the supply chain network.

Step 3: Compare the cost of using roadway and railway for each path.

Step 4: Output the cheapest cost and the corresponding transport mode.

Step 5: Record the final decision.

Figure 4-4 Cheapest cost transport mode selection flow chart



The data is measured and compared to each node reachable from the initial node. Then, by following the formula calculation in (4.2), the cost of railway and roadway is weighted on the graph, and those weights are applied as the distance along the edges in the graph. The cheapest cost and transport mode for each path within the supply chain network are thereafter selected and recorded.

$$C_{ij} = \min\left(C_{ij},\ C_{is} + C_{sj}\right),\ \ i,j = 1,2,3,\dots,10 \qquad (4.2)$$

where

C_{is} and C_{sj} represent transport cost for each path between i,j.

In the next stage, the study runs the decision simulation by assuming to block node 8 (Wuhan) because a catastrophic event occurs and brings a disconnection between node 8 and other nodes. In this way, the impact parameter (ǯ) can be calculated by considering the effectiveness of with- and without- the ITP project:

$$\text{Impact}(ǯ) = \frac{(\text{Cost}_{no-ITP} - \text{Cost}_{ITP})}{\text{Cost}_{no-ITP}} \quad , \qquad (4.3)$$

where

Cost_{ITP} is the cost of goods movement with a resilient project;

Cost_{no-ITP} is the cost of goods movement without a resilient project.

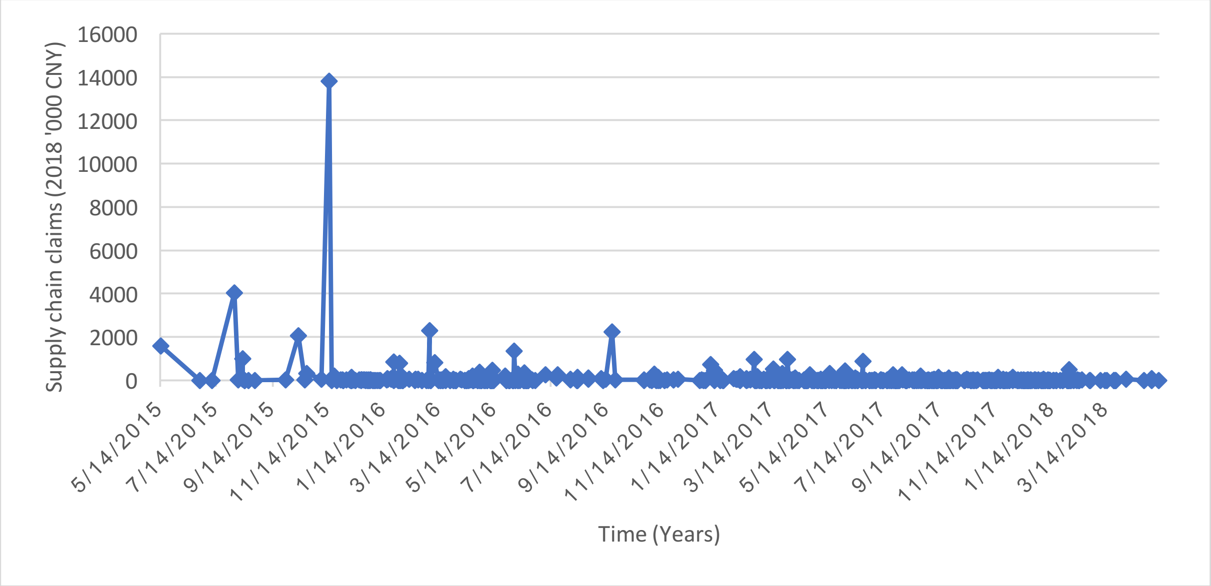
The final pricing model for the supply chain resilience bond will combine the consideration of the impact factor in (4.3) in the resilience bond valuation method in Eq. (3.15).

4.4 Data description

The data source on supply chain catastrophic disruption claims is provided by Willis Tower Watson (Shanghai). Thanks to Willis Tower Watson (Shanghai) for the kind support with the historical supply chain insured claim data. Insurance companies generally keep client data for three to four years; these data are used to evaluate the premium. The dataset is a compilation of 691 insurance claims providing dates of the events, description of events, and amounts of losses from 2015 to 2018. Using the historical data, the study has estimated the frequency and severity of events, and these valuations have allowed us to design the supply chain resilience bond pricing model. The claim amount in the dataset will be converted to the 2018 price level through the use of the consumer price index.

The Willis Tower Watson (Shanghai) dataset shown in figure 4-5 depicts the supply chain disruption claims between 14 May 2015 and 14 March 2018. The highest loss took place on 14/11/2015, when cargo ships collided, resulting in approximately 14 million *yuan* in losses. The study later uses the dataset to simulate the distribution of the consequences of the supply chain disruptions.

Figure 4-5 Supply chain claim data, 2015-2018



Note: Claims have been adjusted to the 2018 currency value level.

In Table 4-1, one can observe the top 10 costliest claims and disruption events in the dataset. These events occurred in different periods, and the value of the claims varies due to differences in time and value. Therefore, the value of the claims has been discounted to the 2018 worth after adjusting for currency inflation.

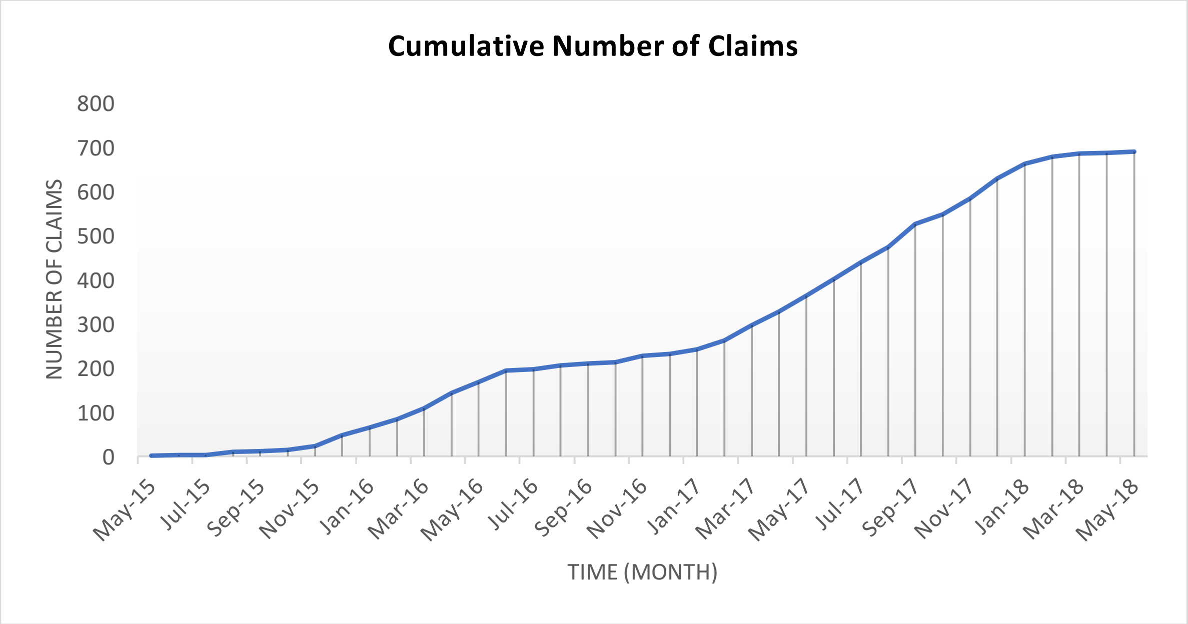
Table 4-1 Top 10 claims from the dataset

Disruption Event	Date	Claims '000(¥)	2018 worth '000(¥)
Cargo ship collision	14/11/2015	13000.0	13814.2
Cargo ship flooding	03/08/2015	3800.0	4038.0
Cargo storage equipment failure	12/10/2015	1937.6	2059.0
Tianjin port explosion	12/08/2015	950.7	1010.2
Rain freshwater damage	20/06/2017	870.8	892.8
Water pipe cracking caused by extreme weather	24/01/2016	820.0	857.5
Cargo ship sink is caused by strong cold air flow	09/03/2016	780.0	815.7
Packaging damage	05/01/2017	730.0	748.5
Gantry crane operational error	01/02/2018	500.0	500.0
Fire hazard	02/08/2017	266.0	272.8

Source: Willis Tower Watson (Shanghai)

Figure 4-6 shows the number of occurrences of supply chain disruption events and the cumulative total number of claims. The historical claims data from Willis Tower Watson (Shanghai) are used to define the distribution of the aggregate claim severity X_j. Following actuarial literature, we consider distributions, e.g., General Extreme Value distribution, Inverse Gaussian distribution, Lognormal distribution, and Weibull distribution. The claims data is fitted into the aforementioned distributions and then tested by Kolmogorov Smirnov, Anderson Darling and Chi-Squared to find the most suitable distribution for describing the data. Then, we use the Poisson process to forecast the expected number of failure events in the network. Figure 4-7 shows the historical number of claims by month, which is used to simulate the claim arrival process, $N_{(t)}$.

Figure 4-6 Cumulative number of claims



The present research uses two classical Poisson processes to simulate the claim arrival process, e.g., the Homogeneous Poisson and the Non-homogeneous Poisson. The Poisson law for the Homogeneous Poisson Process (HPP) states that a constant increment of the number of claims exists and is independent in a given time. However, the disadvantages of HPP are that the claim number cannot increase or decrease, and disruptions in the supply chain may not be suitable for description by HPP. Consequently, the choice of the Non-homogeneous Poisson process implies a Poisson process with a predictable deterministic intensity parameter, λ. To measure the impact of the resilient infrastructure project, we have simulated supply chain networks by assuming cities as nodes in the network. The connection of each node is based on actual direct rail connections between cities in China.

Tables 4-2 and 4-3 provide the data of the distance and price of moving 1 tonne of general goods between different node cities. The distance and price for rail and road transport data have been collected from the official website.

Table 4-2 Road distance/ price of 1-tonne of goods movement between node cities

km / yuan/ton	Shanghai-3	Hangzhou-4	Nanjing-2	Jinan-10	Fuzhou-5	Hefei-1	Nanchang-6	Wuhan-8	Changsha-7	Zhengzhou-9
Shanghai-3	N/A	198 / 84	313 / 113	824 / 226	868 / 283	N/A	N/A	N/A	N/A	N/A
Hangzhou-4	197 / 79	N/A	315 / 114	N/A	686 / 294	427 / 142	557 / 189	746 / 331	N/A	N/A
Nanjing-2	306 / 107	316 / 109	N/A	645 / 174	N/A	216 / 79	N/A	N/A	N/A	673 / 186
Jinan-10	827 / 252	N/A	647 / 244	N/A	N/A	672 / 179	N/A	N/A	N/A	471 / 177
Fuzhou-5	870 / 232	679 / 185	N/A	N/A	N/A	911 / 324	596 / 205	N/A	891 / 328	N/A
Hefei-1	N/A	411 / 136	217 / 82	658 / 126	907 / 264	N/A	514 / 151	458 / 149	N/A	596 / 164
Nanchang-6	N/A	558 / 159	N/A	N/A	595 / 216	487 / 149	N/A	377 / 110	345 / 127	N/A
Wuhan-8	N/A	746 / 191	N/A	N/A	N/A	458 / 113	377 / 144	N/A	385 / 148	550 / 133
Changsha-7	N/A	N/A	N/A	N/A	902 / 236	N/A	399 / 114	391 / 108	N/A	851 / 185
Zhengzhou-9	N/A	N/A	671 / 169	468 / 147	N/A	604 / 162	N/A	550 / 163	853 / 268	N/A

Source: Google map & Linan Logistics Ltd, China Federation of Logistics & Purchasing (CFLP) http://index.0256.cn/pricex.htm

Table 4-3 Rail distance/price of 1-tonne of goods movement between node cities

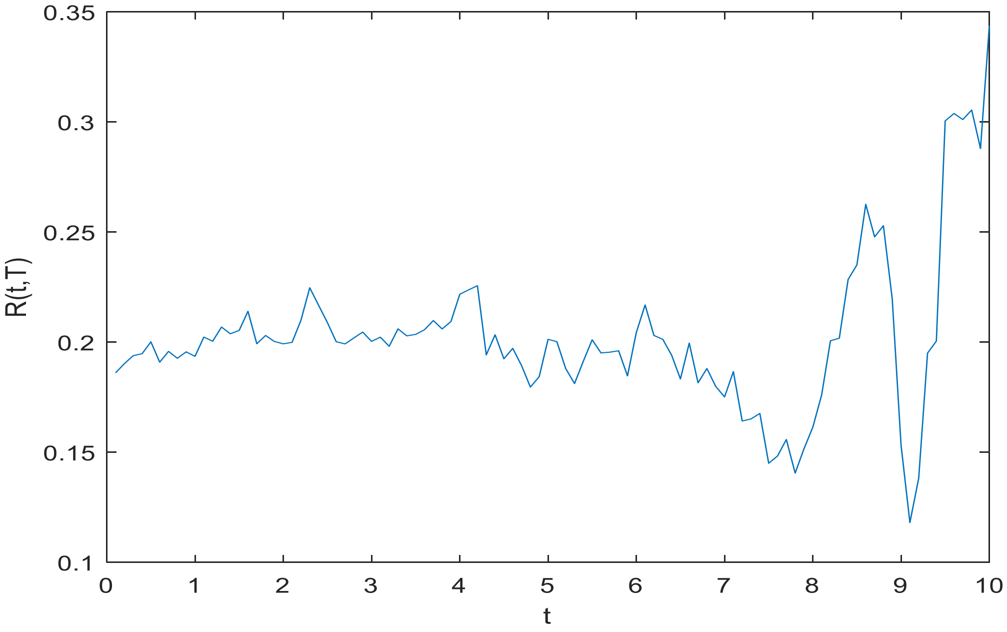
km / yuan/ton	Shanghai-3	Hangzhou-4	Nanjing-2	Jinan-10	Fuzhou-5	Hefei-1	Nanchang-6	Wuhan-8	Changsha-7	Zhengzhou-9
Shanghai-3	N/A	202 / 108	301 / 124	968 / 241	584 / 240	N/A	N/A	N/A	N/A	N/A
Hangzhou-4	202 / 108	N/A	488 / 143	N/A	473 / 204	344 / 155	566 / 184	638 / 217	N/A	N/A
Nanjing-2	301 / 124	429 / 143	N/A	667 / 188	N/A	156 / 120	N/A	N/A	N/A	697 / 197
Jinan-10	968 / 241	N/A	667 / 188	N/A	N/A	614 / 183	N/A	N/A	N/A	668 / 168
Fuzhou-5	612 / 240	455 / 204	N/A	N/A	N/A	492 / 265	581 / 169	N/A	518 / 232	N/A
Hefei-1	N/A	445 / 155	254 / 120	614 / 183	494 / 265	N/A	462 / 153	608 / 168	N/A	602 / 180
Nanchang-6	N/A	764 / 185	N/A	N/A	581 / 169	462 / 153	N/A	344 / 136	419 / 145	N/A
Wuhan-8	N/A	411 / 217	N/A	N/A	N/A	360 / 168	344 / 136	N/A	398 / 146	585 / 161
Changsha-7	N/A	N/A	N/A	N/A	410 / 232	N/A	419 / 145	262 / 146	N/A	898 / 235
Zhengzhou-9	N/A	N/A	697 / 197	668 / 168	N/A	730 / 180	N/A	580 / 161	898 / 235	N/A

Source: Rail Tickets (Huochepiao), http://www.huochepiao.com/ & China Railway, https://www.12306.cn/yjcx/

4.5 Results

The interest rate process is measured with the Cox–Ingersoll–Ross (CIR) model. However, we will consider that the dataset period of interest rate need not match the insurance loss data because the catastrophe risks are independent of financial risks (Shao et al. 2017). By implementing the method from the author (ibid), the 12-month LIBOR historical rate from 2000 to 2011 is applied to calibrate stochastic interest rate parameters, where the reverting speed $\mathrm{k} = 0.2124$, average interest rate $\theta = 1.0847$, and the volatility $\sigma = 42.0791\%$. The initial value of $r_0 = 1.13\%$ was the actual LIBOR rate in Dec-2011 and the market price of risk γ_r was a constant -0.01. In accordance with Eq. 3.2 in chapter 3, the dynamic interest rate is estimated by combining the parameters. Figure 4-7 illustrates the forecast for the dynamic interest rate in the following 10 years based on historical data from LIBOR.

Figure 4-7. Estimated 10-year stochastic interest rate based on LIBOR



Apart from the dynamic interest rate, the dynamic claim is another main part of the pricing model. The dynamic claim process is measured by the Poisson process. The Poisson process describes the frequency (N_t) of occurrence in catastrophe risk derivatives. From the observation of the trend of the catastrophic disruption, we are unable to clearly define the irregular trend of the occurrence. We therefore select a homogeneous Poisson process for the catastrophic disruptions, with a monthly intensity $\lambda = 18.6486$. To define the distribution of the claim severity, (X_j), the historical data is fitted in Lognormal, Inverse Gaussian, Generalised Extreme Value, and Weibull distribution. As shown in table 4-4, the tests from Kolmogorov Smirnov, Anderson Darling and Chi-Squared indicate that the goodness of fit is the Lognormal distribution, which is the most appropriate distribution for describing the supply chain insurance claims data from Willis Tower Watson (Shanghai).

Table 4-4 Tests of goodness of fit

#	**Distribution**	**Kolmogorov Smirnov**		**Anderson Darling**		**Chi-Squared**	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.11119	3	25.374	2	101.26	2
2	Inv. Gaussian	0.29075	4	255.86	4	N/A	
3	Lognormal	0.03368	1	2.968	1	31.085	1
4	Weibull	0.09965	2	35.433	3	172.84	3

Since Lognormal distribution has been ranked as number 1, it will be assumed as the distribution of the claim occurrence. By fitting the data, the parameters σ=1.8568, μ=1.8542 are applied in the supply chain resilience bond pricing model.

Table 4-5 shows the cheapest cost for each path and the corresponding transport mode to move 1-tonne of goods between node cities. In the next step we calculate the cheapest combination route to move 1-tonne of goods from Changsha (node 7) to Shanghai (node 3); it will be found by using the shortest path problem in this simulation.

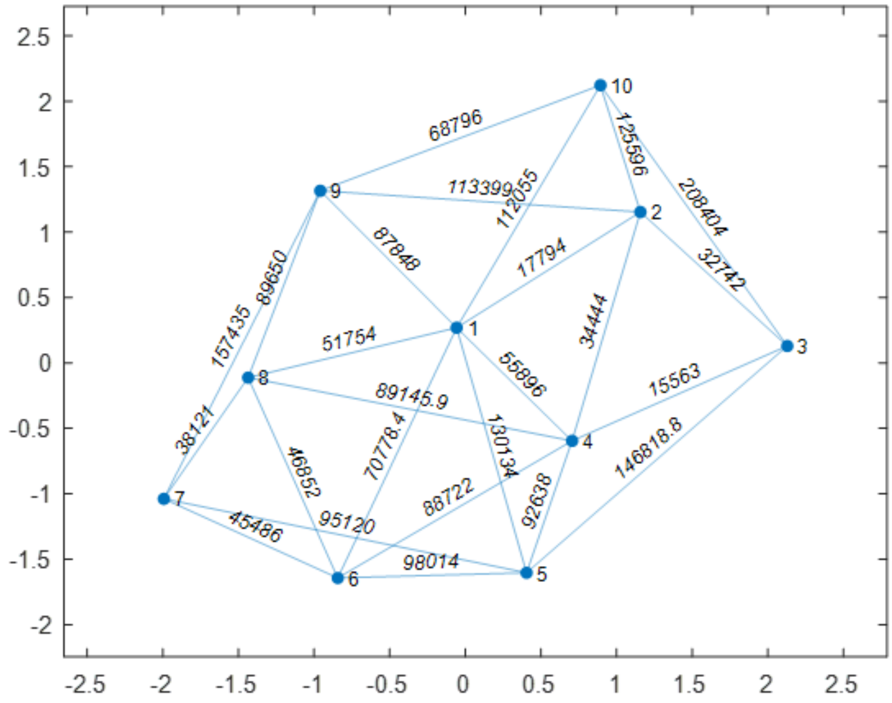
Table 4-5 The cheapest cost and transport mode between node cities

Note: (Rail = rl, Road = rd)

yuan / mode	Shanghai-3	Hangzhou-4	Nanjing-2	Jinan-10	Fuzhou-5	Hefei-1	Nanchang-6	Wuhan-8	Changsha-7	Zhengzhou-9
Shanghai-3	N/A	16,632 / rd	35,369 / rd	186,224 / rd	140,102 / rl	N/A	N/A	N/A	N/A	N/A
Hangzhou-4	15,563 / rd	N/A	35,910 / rd	N/A	96,303 / rl	53,286 / rl	104,370 / rl	138,382 / rl	N/A	N/A
Nanjing-2	32,742 / rd	34,444 / rd	N/A	112,230 / rd	N/A	17,064 / rd	N/A	N/A	N/A	125,178 / rd
Jinan-10	208,404 / rd	N/A	125,596 / rl	N/A	N/A	112,055 / rl	N/A	N/A	N/A	83,367 / rd
Fuzhou-5	146,819 / rl	92,638 / rl	N/A	N/A	N/A	130,134 / rl	98,015 / rl	N/A	120,176 / rl	N/A
Hefei-1	N/A	55,896 / rd	17,794 / rd	82,908 / rd	130,663 / rl	N/A	70,778 / rl	68,242 / rd	N/A	97,744 / rd
Nanchang-6	N/A	88,722 / rd	N/A	N/A	98,015 / rl	70,778 / rl	N/A	41,470 / rd	43,815 / rd	N/A
Wuhan-8	N/A	89,146 / rl	N/A	N/A	N/A	51,754 / rd	46,853 / rl	N/A	56,980 / rd	73,150 / rd
Changsha-7	N/A	N/A	N/A	N/A	95,120 / rl	N/A	45,486 / rd	38,121 / rl	N/A	157,435 / rd
Zhengzhou-9	N/A	N/A	113,399 / rd	68,796 / rd	N/A	97,848 / rd	N/A	89,650 / rd	210,581 / rl	N/A

Figure 4-8 represents the network of the evaluation cost for different routes. The analysis of the network allows us to estimate the cheapest combination route to move 1-tonne of goods from Changsha (node 7) to Shanghai (node 3), which are the routes 7-8-1-2-3, with the total cost of 140,411 yuan. The transport modes are the railway to move goods from 7 to 8, then changing to the roadway from 8-1-2-3. We can now summarise our results that the cheapest cost for moving goods from node 7 to node 3 is 140,611, where an interchange on node 8 brings an additional 200 yuan charge. Then, by simulating a catastrophic event that triggers a failure of node 8, the new cheapest combination route for moving 1-tonne of goods from node 7 to node 3 changes to 7-6-4-3, with the total cost of 149,771 yuan for using roadway only for each path.

Figure 4-8 Cheapest cost route selection



Hence, the impact factor (ǯ) of node 8 to the whole supply chain network can be computed using Eq. (4.3):

$$\text{Impact}(ǯ) = \frac{(149{,}711-(140411+200))}{149711} = 6.07\%$$

This result demonstrates that the intermodal transportation port (node 8) is crucial as a cost reducer in the movement across the supply chain because it can induce a 6.07% cost reduction to the supply chain goods movement. The reduction is passed on to costs for supply chain recovery from disasters, where the post-disaster recovery cost will be reduced by 6.07%.

4.5.1 Supply chain resilience bond pricing

When pricing resilience bonds, the difference in the expected losses will be measured when the catastrophe occurs with/without the project. In other words, as above in Eq. 4.4, the difference will be captured as the rebate to invest back into building a resilient project, i.e., if the ITP node 8 does not exist in the supply chain, the rebate fund will be used to reinforce the port. Therefore, in the severity of the losses we can consider a 6.07% reduction because node 8 is a resilient project that will lead to a reduction in losses across the supply chain. To verify the robustness of our finding, we generate 100,000 simulations to calculate the price of a 5-year resilience bond for the supply chain. We assume the proportion of the face value (ρ) repaid to investors is equal to 0.5, and the threshold of the bond is within [2, 10] million *yuan*. The price of the supply chain resilience bond is shown in figure 4-9; the bond value is varied under different conditions. By considering the resilience level of 6.7% with the ITP project, threshold and time are the factors that lead to different prices. At the lowest trigger 2 million *yuan* within the initial purchase period, the bond price is at the lowest point. However, along with the increasing of the trigger value, when the supply chain resilience bond reaches maturity at 5 years, the bond price will attain its highest price over the face value. In addition, during the same year, the higher the threshold value, the higher the bond price will be. Similarly, under the same threshold value, the longer the bond investor holds the bond, the higher the price will be due to the reduction of the risks. In figure 4-10, by considering the resilience level equals 0, the same as the catastrophe bond, the similar patent is found with the resilience bond. When the investors hold the bond to maturity at year 5, the bond prices increase along with the rise of the threshold value. Therefore, the highest price of the catastrophe bond will be at year 5 under the threshold of 10 million *yuan*.

By comparing figure 4-9 with 4-10, the price of the resilience bond for the supply chain at maturity year 5 will be 66.8 *yuan* over the face value of 100 *yuan* when the threshold is around 10 million *yuan*. At the same level of threshold and maturity time, if there is no investment in an ITP resilient project for the supply chain network, the price of the catastrophe bond is 60.4 yuan. Using the formula Yield $= (\frac{Future\ Value}{Purchase\ Price})^{\frac{1}{n}} - 1$, (n = years to maturity), the yield of a 5-year-maturity resilience bond for the supply chain is 8.41% with the ITP project and 10.61% without the project. The quality of a bond depends on the quality of the sponsor, which means a higher yield bond is more likely to be issued by a higher default risk insurance company.

From the result, we also find that the 6.07% effectiveness of a port will generate a reduction of 2.2% returns by switching from CAT bond to resilience bond.

Figure 4-9 Five-year supply chain resilience bond price with the ITP project

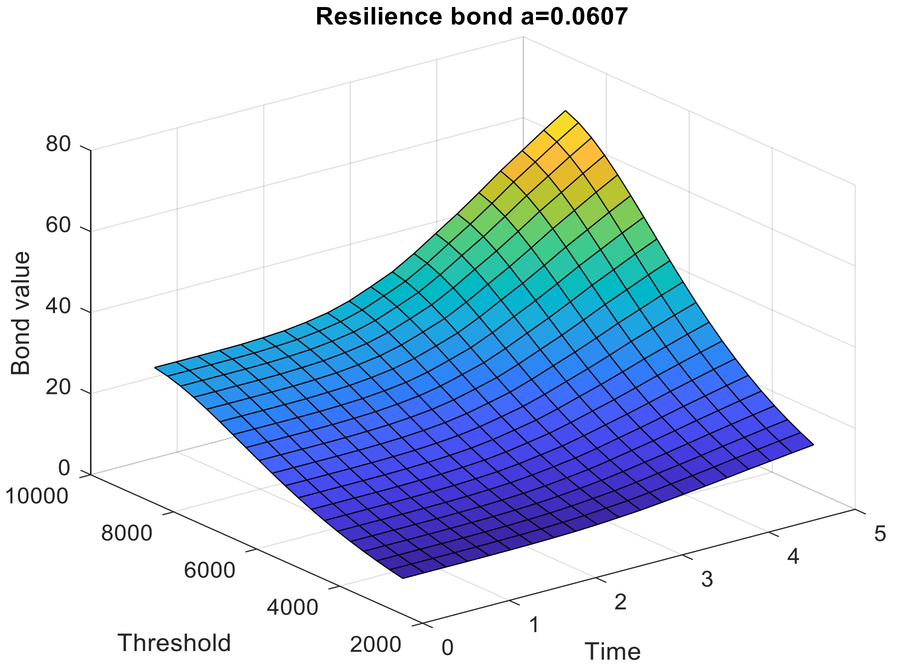
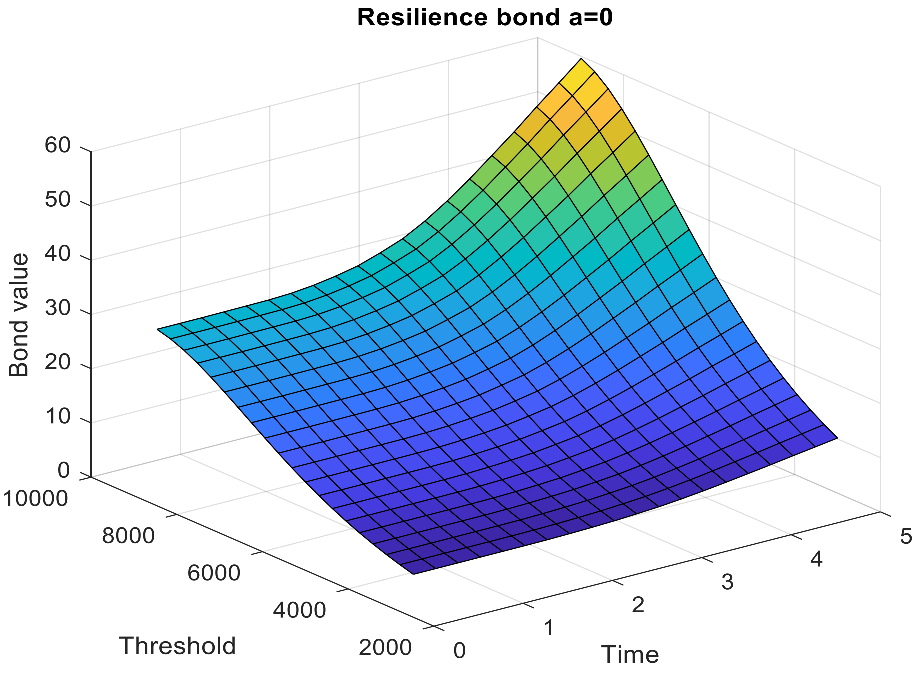


Figure 4-10 Five-year supply chain resilience bond price without the ITP project



4.6 Conclusion

This chapter has examined the importance of the supply chain by focusing on the impact of one node in the event of a catastrophe, rather than considering a collapse of the whole supply chain network from a mega catastrophe. Nevertheless, we can reach some conclusions. A financial market is a place containing enormous potential capacity to absorb the risks from catastrophic events. As a newly proposed bond, the resilience bond brings more advantages for managing catastrophic risk than the catastrophe bond. In the case study presented here, two main findings are worth noting: firstly, we observe that a resilience bond with a resilient project has a lower yield than the CAT bond without the project. The resilient project can mitigate the long-term physical risk for the whole supply chain network where there is an additional gain for the supply chain network. Furthermore, the resilience bond with a resilient project also reduces the default risk for the sponsor and lowers the investment risks for investors. The catastrophe bond is usually rated as BB and B level bond, which in general is lower than the recommendation of investment level. Therefore, the catastrophe bond brings several advantages to investors. However, the resilience bond has lowered the risk of the probability of default due to a resilient project, which will mitigate the risk of collapse and economic losses. In this way, it reduces the risks for investment, and may reach a higher rating score than catastrophe bonds.

Secondly, the performance of the eligible resilient project brings significant impacts to the price in addition to the dynamic interest rate and losses. The current spreads of the catastrophe bond and resilience bond are more related to the historical losses and interest rate. However, the result of this case study proves that the performance of a resilient project is the core impact parameter to the price of the resilience bond. It shows that the price of a resilience bond mainly depends on the effectiveness of a resilient project. Furthermore, we notice that the resilience bond could also be a good financial tool for the government to improve infrastructure. The rebate funds in the resilience bond could bring an incentive to the development and protection of a country’s infrastructure system. In the next chapter, we use the example of the Towyn flood of 1990 to analyse the effects of the resilience bond in the development of resilient flood infrastructures; in so doing we identify the influential factors for valuing the resilience bond.

Chapter 5 Financing Flood Resilient Defence Infrastructure via Resilience Bond: A Case Study of Towyn, Wales

5.1 Introduction

As the world is getting warmer, the melting speed of Arctic sea ice has exceeded the expectations of climatologists and other scientists and should therefore not be ignored (Ebinger and Zambetakis 2009). The quickening of climatic and hydrological changes is endangering societies and the environment, resulting in sea level rises and increased frequency and consequence of flooding in many areas (Bronstert 2003; Douglas 2009). A MetOffice (2020) (2020) report recorded that, when the storm Ciara hit the UK and Ireland, it brought heavy rainfall, with up to 97 mile-per-hour winds, triggered around 190 flood alerts, cut power supplies for approximately 25,000 homes, and drowned 500 properties. According to McGranahan et al. (2007), sea levels may rise beyond 10 metres in the foreseeable future, making 10-metre elevation a safe height margin in regard to flooding. However, approximately 450 million people around the world are exposed to under 10 metres above sea level and are living within 100km of coastal areas (Lichter et al. 2011).

The severity of the problem of millions of people being exposed to increasing flood events inevitably requires funding for the preparedness and recovery projects. In previous decades, when weather events were largely spaced apart in time, victims of flood events were only assisted by governments through loans and grants, thereby imposing a heavy burden for public resources (Brody et al. (2017). Private insurance companies eventually stepped in to become one of the most efficient and widely used risk management tools for hedging exposure to risks, such as storms, earthquakes and floods. However, in recent years, a higher frequency of unexpected catastrophes has caused massive insurance losses and led to unprecedented reimbursement obligations to the (re)insurance industries. According to SwissRe (2018b), around 30% of catastrophic events around the world are related to floods in the 40 most costly insurance losses catastrophic events occurring between 1970 and 2017. For example, Hurricane Andrew in 1992 cost $16 billion in insured losses, and the huge insurance reimbursements that followed after the catastrophe have bankrupted up to 60 insurance companies (Muermann 2008). To mitigate the risks, Insurance-Linked Securities (ILS) represent the bridge between conventional insurance and the capital market rather than solely relying on traditional (re)insurance companies (S. H. Cox and Pedersen 2000). Promoting catastrophic risk securitisation has become one of the newest approaches to convey the insurance risks to the capital market and to leverage additional funds from capital market investors to cover insurance obligations (Torre-Enciso and Laye 2001).

However, Schelfaut et al. (2011) show that the risks from catastrophic events cannot be eliminated, especially from flood catastrophes; therefore, focus should be on the mitigation of the impacts to communities and towards improving the resilience of existing flood systems. Bruneau et al. (2003) argue that shortening recovery time, and thus reducing the probabilities and consequences of failures from flood infrastructures, will strengthen the resilience of a system and lessen unpredictable impacts. A resilient flood defence should continue to deliver its core function when faced with unexpected catastrophic flood events. Improving resilience by frontloading preparation to enhance the flood infrastructures to resist unforeseen catastrophes is likely to allow extra time for the catastrophe assessment, and in so doing, lead to successful adaptation of existing flood defences. However, most flood defence infrastructures around the world rely on public sector funding. The UK government has invested £2.6 billion since 2015 in cooperation with the Environment Agency and partners for flood defence (HM-Government (2020). The investment has improved the protection for 300,000 homes across England by offering more than 1,000 coastal and flood defence schemes. The UK government has also spent £1 billion between 2015 and 2020 to maintain its flood defences, the cost of which has increased by approximately £200 million in five years. The UK government plans to double its investment in flood and coastal defence programs in England to 5.2 billion in the six years after 2021.

Attention is therefore turning to the bond to fill the infrastructure finance gap, according to research by Hyun et al. (2008), who argue that bond investments are efficient options for a broad range of investors from the capital market. In the present thesis, a flood resilience bond is proposed as an alternative, in which government attracts private investors into the development of flood defence infrastructure projects. Two distinctive features of the resilience bond are that it has the same insurance function as a catastrophe bond which compensates victims after unforeseen catastrophes, and that it generates rebates to invest back into eligible resilient projects, especially the resilient infrastructure-based flood defence projects (Re:Focus 2015). As mentioned above, in regard to this newly proposed bond in the market, few pricing models and applications of its type have been published. Therefore, a flood resilience bond pricing model and case study is proposed in this chapter; to price it fairly in the market, we have selected the town Towyn in North Wales as our case to test and verify the mechanism of the flood resilience bond. Towyn is thereafter used in the analysis of flood-related experiments which show significant test results for flood resilience bonds. We use the event in the past because as De Bruijn (2004) concludes, the impacts from flooding events and flood recovery may not be reflected in the currently available data, since flooding is a low-frequency event and the database is usually incomplete. Under the condition of incomplete database, it is problematic to accurately value catastrophic flood risks that lead to rare models that can price the flood-related bond precisely.

The chapter is structured so that section 5.2 provides reviews of flood risk management and insurance securitisation in the flood defence system, the issue of the resilient infrastructure-based flood defence project, and the impact comparison review of green bond and resilience bond. Section 5.3 introduces the design of the mechanism for the Towyn flood resilience bond. Methodology section 5.4 elaborates the testing of the pricing model using simulated data from the Towyn historical database. Sensitivity analysis and discussion are given in section 5.5.

5.2 Background

Flooding is generally defined as, “the rising of the water that overflows onto dry land.” In recent years, extreme flooding has increased in the UK; three persistent heavy rainfalls in the summer of 2007 led to the worst flood event in 60 years, killing 13 people, trapping almost 7,000 people, and impacting about 55,000 properties (Blackburn et al. 2008; Mendoza-Tinoco et al. 2017). A mere two years after major flood events in 2013/2014, the winter from December to February in 2015/2016 was reported as the second wettest winter in the UK, with rainfall accumulations reaching several new records (Barker et al. 2016). As the frequency of catastrophes, such as floods, weather disasters, heat waves, and forest fires increases, climate change is being blamed as the main culprit (Nema et al. 2012). But Robson (2002) argues that there is no clear evidence to show that flooding is directly affected by climate change. Robson says notable evidence proves that the influence of climate change on rainfall is more significant than the impact of flooding. According to B. Bates et al. (2008), several factors such as rainfall, snow and melting ice cause flood events. The drainage basin condition is also a major factor in flooding, e.g., existing level of water in rivers, coverage of ice and snow, characteristics and status of soil, urbanisation rate, and performance of defences and reservoirs. In opposition to Robson (2002), Wheater (2006) asserts that, even though the impacts from climate change between countries are highly variable, there is consensus that the changing climate is the main reason for warmer and wetter winters in the UK, which have thus been identified as scenarios of flood risk.

5.2.1 Flood risk management and insurance securitisation

It is widely recognised that understanding flood risk is key to enhancing risk management because flood risk cannot be eliminated (P. Sayers et al. 2002). Risk management is gaining popularity in flood research as the more suitable strategy to deal with risks from natural hazards, especially flood risks (Plate 2002; Schanze 2006). The UK began its Flood Risk Management program (FRM) in 1990, emphasising the soft engineering methods and flood management strategies in the design and construction of flood defences (Butler and Pidgeon 2011). The purpose of an FRM is to provide comprehensive control of risks from flood events, thereby minimising the influence of flooding and protecting residents from inundation. According to Hegger et al. (2014), there are five types of flood risk management strategies:

- First are flood defences. Infrastructure-based barriers such as embankments, dams and dikes are the general national and regional level strategy, which is to maintain a distance between residents and flood water.
- Second is flood risk prevention. Building properties away from flood zones is the general governmental and private level strategy, which is recognised as proactive spatial planning to keep people away from flood areas.
- Third is flood risk mitigation. Designing and constructing flood-proof properties and measuring the spatial orders is generally the resident, water manager and project

promoter level strategy, which can directly mitigate the consequences of catastrophic floods.

- Fourth is flood preparation. The development of the flood alert and evacuation system is typically the regional authority and local government level strategy, which prepares the society for unexpected flood events.
- Fifth is flood recovery. Seeking insurance services and planning for post-catastrophe recovery is normally a government and insurance level strategy, which saves recovery time for the people affected by the catastrophe.

As an efficient management tool in the recovery of societies from flood events, insurance services are applied to help plan and hedge the post-catastrophic risks from flooding. Penning-Rowsell et al. (2014) show that insurance not only provides unusual stability to the policy for many years, but also releases the government from the national flood loss compensation scheme. Flood insurance services can effectively enhance the development of catastrophe-prone areas because it offers reimbursement to support and accelerate the post-disaster reconstruction and recovery of the economy. However, flood insurance may not generate benefits due to the low probability of occurrence of flooding events. Browne and Hoyt (2000) state that a large number of properties around the world remain in uninsured status from flood catastrophes. Lamond et al. (2009) discuss how scientists have forecast that climate change has caused growing threats from severe weather events, so insurance companies are proactively working with the research community and government to understand, quantify and manage the risks. Flood insurance services can efficiently transfer the asset owners' risks from natural disaster to the third party instead of bearing all the unpredictable losses.

As per Michel-Kerjan and Kunreuther (2011), insurance has been used widely around the world, the insurance industry is booming in high-income countries to cope with catastrophic flooding events. On the contrary, some low-income nations are still solely reliant on international and local government aid. Moreover, insurance services vary, depending on the country; for example, the main flood insurance providers are private insurance companies such as the UK and Germany, but in the U.S., the National Flood Insurance Program (NFIP), one of the largest flood insurance providers, is operated by the federal government. Nevertheless, as reviewed by Lamond et al. (2009), private insurance companies are the main funders in the reinstatement of flooded residential assets in European countries. Many private flood insurers are hesitant to offer insurance services for flooding risks, given the increasing frequency of floods and higher costs incurred in recent years. Although a flood is a low probability event, it usually causes high consequences when it does occur; insurance companies may only benefit in the short-term because unforeseen economic losses could collapse the insurance industry and cause default risks for (re)insurance companies. Based on research by Bennett and Hartwell-Naguib (2014), frequent inundation puts almost 5 million properties at risk at a cost of £1.1 billion of losses annually in the region; they predict that unforeseen inundation damages will reach £27 billion by 2080. To improve the capacity of the insurance industry to bear more risks from natural hazards, insurance securitisation is coming to the fore; this alternative tool aims to uncover the potential of capital markets and transfer risks to investors. According to Froot (2001), the simulation from USAA shows that the design of insurance risk securitisation reduces the program cost when compared to traditional insurance industries. As a new risk management tool, securitisation of insurance risks not only expands the capacity to the whole insurance industry in transferring risks from catastrophic events to the capital market, but it also creates more innovative insurance contracts for insurance industries to hedge the risk of varied catastrophic events.

5.2.2 Enhancement of flood defence infrastructure

Flood defence infrastructure can be defined as resilient construction and, as such, a systematic component of an integrated flood risk management strategy. The improvement of flood defence infrastructures is an integral strategy for reducing damage from flooding and speeding the recovery process (Golz et al. 2015; Proverbs and Lamond 2017).

The term 'resilience' first emerged in studies of the ecosystem and its capacity to persist despite catastrophes (Crawford S Holling 1973). Holling later widened the definition of resilience to the engineering field to indicate the recovery speed of a system to its equivalent original status from unexpected events (Crawford Stanley Holling 1996). Much later, P. B. Sayers et al. (2012) identified vulnerability and uncertainty as essential conditions in the design of resilience in flood risk management and human adaptation. Around the world, countries are recognising the need to build resilient urban systems and communities in the face of unexpected weather events.

For example, Rajabalinejad et al. (2010) show that hurricane Katrina in 2005 significantly damaged the flood defence system in New Orleans, alerting the population that more reliable barriers were needed. Batica and Gourbesville (2016) suggest that a resilient flood system and community should be able to live with catastrophic floods, deliver its core function continuously before and after catastrophic events, bounce back quickly to its equivalent status, and build a database for future unknown events. Steenbergen et al. (2004) define appropriate flood defence as composed of different barriers in accordance with local surroundings, such as higher ground, dunes, dikes, levees, locks, and sluices. Not only should an appropriate flood defence be able to absorb damages and minimise impacts on societies, but it should also be able to return quickly to its original status.

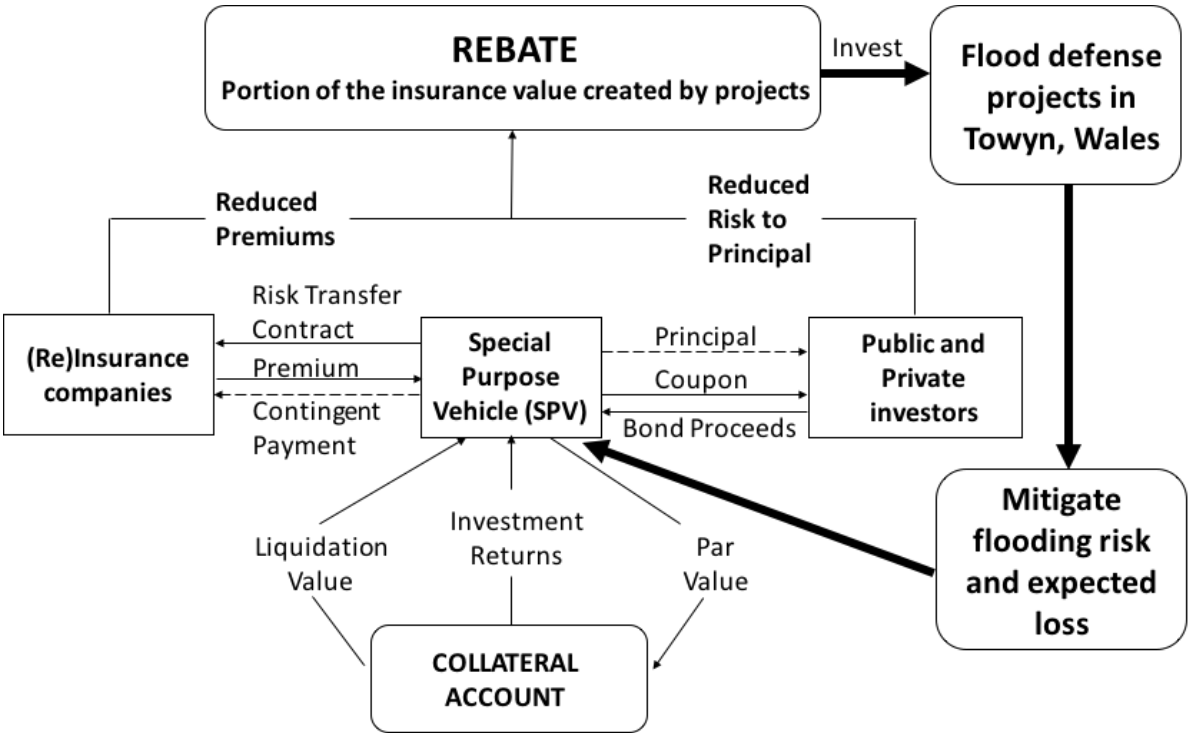
Therefore, the concept of 'resilient infrastructure' emerging in markets among both public and private sectors in different societies, aims to improve the resilience of infrastructure-based systems to resist natural disasters rather than simply construct and maintain infrastructures (Mizutori 2019). With greater attention being given to the connections between systems, resilient infrastructure-based flood defence is preferred, for example, when breaching occurs, where frontloading preparedness has been taken in advance to reduce economic losses and save recovery time. In addition to the physical enhancement of infrastructure-based flood barriers, hybrid flood barriers are also effective approaches that combine, e.g., flood defence infrastructures with salt marshes (Marijnissen et al. 2020; Siemes et al. 2020). Geographical Information Systems (GIS) have also been added to the flood defence system to analyse the risk maps of a flood to help identify system weaknesses and raise alerts for action when necessary (Plate 2002).

Joseph et al. (2014) show how resilience can be part of the overall integrity of large-scale infrastructure-based flood defences and can mitigate the worst effects of flooding. However, as Proverbs and Lamond (2008) lament, although building resilience has become a 'hot topic' around all flood forums, it has been minimally applied due to funding concerns. Most communities tend to consider flood defences as 'public goods' and believe that government should be responsible for the resilience enhancement and protection of their properties from flood waters because the governments are recognised as the most important investor and protector (Glomm and Ravikumar 1994; Munnell 1992). For example, R. Dawson et al. (2004) demonstrate that the construction, operation, and maintenance of flood defence infrastructure has occupied a high percentage of government expenditure in its flood risk management strategy. Such infrastructure projects, however, strain government budgets due to high opportunity costs in the development of societal projects. According to Bennett and Hartwell-Naguib (2014), maintenance costs of current flood defences will rise to over £1 billion annually by 2035. The shortfall in spending has led the UK government to introduce a new flood defence funding system and expects increased private investment going forward. Effectively, say Larsen et al. (2019), bonds offer opportunities for both private and public sectors to borrow money from capital market investors at low cost. Already, resilience bonds have been recognised as efficient financial tools for raising money for infrastructure projects, e.g., upgrading flood barriers and building early warning systems. A so-called 'double glazing' strategy, that combines insurance services with the development of resilient infrastructure-based flood defences, is expected to protect residents in flood prone areas. Therefore, along with the increasing demand for building resilience in advance, the resilience bond brings more potential advantages through both post-disaster reimbursement and upfront investment funding in resilient projects.

5.3 Flood resilience bond: A case study of Towyn, Wales

Towyn is located in North Wales. According to Brockway (2020), Towyn suffered a devastating flood due to low atmospheric pressure, high-level tides, and strong onshore winds on 26th February 1990. The 1990 Towyn flood was classified as a rare event, with a probability of occurring once every 500 years. The flood caused significant damage, breached the railway embankment, poured into the streets, and impacted 2800 homes. Approximately 5000 people had to be evacuated (P. D. Bates et al. 2005). When we look closely at this devastation flood event in 1990, we observe its long-lasting influence on Towyn and on the people living near the coast. The ferocity of the event caused Towyn's flood defences to breach, as the storm coincided with hide tide, and the water surged to around 1.5 metres. Helicopters and lifeboats were brought to rescue and evacuate people because the flood had swept across the railway and flooded caravans and houses. The damage wrought by the Towyn flood, and more recent occurrences of flooding events, has motivated coastal residents to demand greater protection and resiliency of their town, their homes, and their livelihoods. Figure 5-1 depicts the mechanism proposed for the issuance of resilience bonds in flood resilient infrastructure projects.

Figure 5-1 Flood resilience bond mechanism for Towyn



Source: Adapted from (Re:Focus 2015).

Three main functions, e.g., insurance services, rebates and investment characterise the flood resilience bond mechanism. The insurance function is similarly designed as the traditional CAT bond. For example, coastal residents in Towyn could seek out services from the insurance market and pay a premium in exchange for repayment contracts for flood events. To share the unforeseen risks, the Special Purpose Vehicle (SPV) issues a flood resilience bond on behalf of (re)insurance companies to bridge the gap between the insurance market and the capital market. Insurance companies benefit from the issuance of resilience bonds because investor purchases of the bond have expanded the repayment capability for insurance companies to diversify the risks. The unique feature of the flood resilience bond is that it generates a rebate based on the risks reduced from the whole system, which is then reinvested to support the construction and maintenance of Towyn's resilient flood defence projects. The risk reduced from the proposed resilient project is assessed in advance and transferred to the fund (rebate); the fund is then used to support the development of the project. Potential investors could be entities affected by unexpected flooding events, e.g., residents, communities, local authorities, and related infrastructure sectors. An application of the resilience bond to the case of Towyn may efficiently enhance the resilience of the flood defence through adequate funds generated by the resilience bond. In the flood resilience bond the upfront funds can ensure the development of resilience enhancement to the flood defences, thus lowering negative impacts. In addition, the flood resilience bond may bring all related entities together in dedicated support of the development of resilient flood defence. Therefore, the present study uses specific data from Towyn's historical database to test the proposed flood resilience bond.

5.4 Methodology

The model we apply here, and which is deemed most efficient for calculating the expected price of resilience bonds, tends to follow the following processes: a stochastic model is applied to analyse the time-series data, measure the instantaneous interest rate, and generate random catastrophic events; next, a compound Poisson process is applied to describe the economic losses from flood events. For example, the insurance losses from the breaching of any specific flood defences under specific surge height will be simulated and computed. In addition, a resilient infrastructure-based flood defence project is assumed capable of mitigating the expected losses in Towyn. As an alternative financial tool to support resilient projects, a rational pricing model can provide guidance on a fair market price that attracts more investors from the capital market.

5.4.1 Frequency and severity distribution of Towyn catastrophic flood losses

In the flood insurance field the dynamic loss is changed by either surge level or different flood defences breaches. Modelling the dynamic losses and subtracting costs of losses from resilient infrastructure projects are the most significant components of the flood resilience bond, but are also a function unique to resilience bonds and distinguishes them from other bonds. The two main components of the dynamic loss are defined as the counting process of events, $[N_t]$, where $t \geq 0$ and total claim size $\left[X_j\right]$, where $j = 1$. Therefore, the cumulative catastrophic flood losses at period t is modelled by

$$L_T = \sum_{j=1}^{N_t} X_j \,, \quad t \in (0, T), \tag{5.1}$$

where, L_T is the aggregate loss, $L_T = 0$ if $N_t = 0$; $N_t, t \in (0, T)$ follow the Poisson process that indicates the occurrence of catastrophic events at the period t. In particular, $P(N_t - N_s = \lambda) = e^{-\lambda(t-s)} \frac{[\lambda(t-s)]^n}{n!}$ in which λ is the intensity of the process.

For the severity of flood events, X_j represents the random variable of the cumulative post-flooding economic losses distribution. The cumulative distribution, X_j, is composed of the combination of $X_1, X_2, X_3 \ldots X_n$ with the random frequency of *n* defined by N_t. Therefore, we obtain

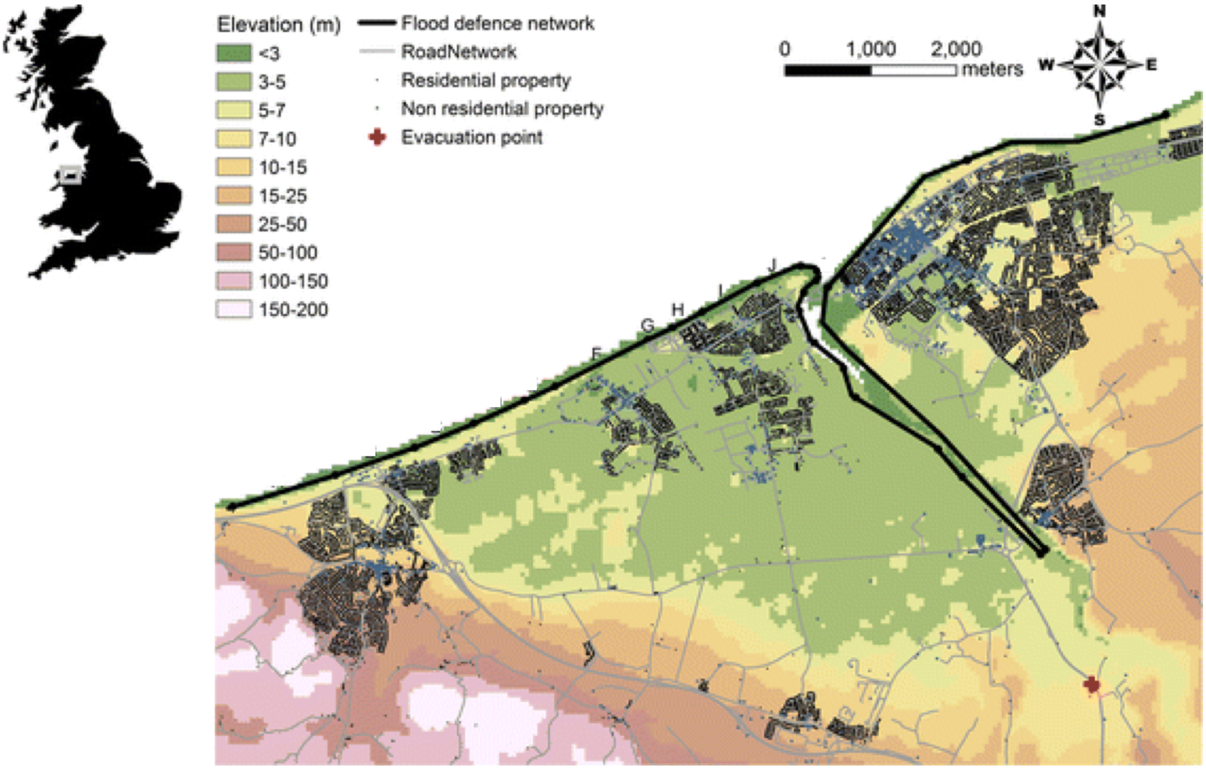
$$L_T = X_1 + X_2 + X_3 +, \ldots, + X_n = \sum_{j=1}^{n} X_j \qquad (5.2)$$

The losses of $X_1, X_2, X_3 \ldots X_n$ indicate the severity for each independent event. However, the lack of data issue will lead to an impact on the process of the valuation modelling. The consequences of the flooding events are forecast using the historical data by fitting the data into the suitable distribution; this is a major activity in the pricing model of the resilience bond. Therefore, in this chapter, the simulated data are applied from R. J. Dawson et al. (2011), who have created three-level (4m, 5m, and 6m) surge events and computed the aftermath losses for each independent value of $X_1, X_2, X_3 \ldots X_n$ for Towyn. Furthermore, all catastrophic event losses are nonnegative, independent, and identically distributed values, (X_j), with no event occurring at the same time. Let the distribution function *F(x)* represent the distribution of $X_1, X_2, \ldots, X_j$, where $F(x) = P(X_j < x)$. The simulated data is then fitted by related distributions to calibration of the distortion operator. To find the suitable distribution for describing the data, Kolmogorov Smirnov, Anderson Darling, and Chi-Squared tests are used to test the goodness of fit.

5.4.2 Resilient infrastructure-based flood defences

The design of a flood resilience bond corresponds to a resilient infrastructure project that is able to generate risk reduction across an entire system. A. Z. Rose (2005) discusses the U.S. Federal Emergency Management Agency (FEMA) study in which the cost-benefit ratio shows a high ratio result from the project containing a mitigation project for public utilities. So we assume a resilient enhancement project for the current flood defences in Towyn that can mitigate risks and increase resistance against the different surge levels.

Figure 5-2 Flood defences in Towyn, Wales



Source: Adapted from (R. J. Dawson et al. 2011).

The map in Figure 5-2 depicts the flood defences indicated within Towyn, Wales. To define the resilience factor, we focus on the aftermath losses from the breach of point F, G, H, I, and J flood defences because the part of the town covered by these five flood defences is built within 3 to 5-metres of elevation. According to R. J. Dawson et al. (2011), the economic losses data caused by single and combination breaching from these five flood defences can significantly show the difference between with- and- without- flood defence enhancement project. For example, if one of the five flood defences have the potential to fail, the simulation model creates three-level surges to test the flood defence, and computes economic losses caused by the flooding. In this way, a different combination of flood defence breaches under three levels of surge has been computed and recorded as our database. The simulated database is used to measure the distribution of dynamic losses. Accordingly, a resilient project enhances the flood defence for Towyn, indicating a reduction in the probability of failure during catastrophic flooding. We therefore introduce the impact parameter (ǯ) to indicate the reduction in the percentage of losses from the resilient flood defence project.

In the next step, D_i represents the flood defences and calculates the breach probability of each flood defence under different surge levels. B implies breach events, and S_j is the probability of the level of the surge. Thus, the probability of $p_F, p_G, p_H, p_I\ and\ p_J$ can be calculated separately as

$$P(B|D_i) = \sum_j P(B, S_j|D_i) \tag{5.3}$$

Therefore, by following the Bayes Lemma

$$P(D_i|B) = \frac{P(B|D_i)P(D_i)}{P(B)} = \frac{P(B|D_i)P(D)}{\sum_i P(B|D_i)P(D_i)}$$
$$= \frac{P(D_i)\sum_j P(B, S_j|D_i)}{\sum_i[\sum_j P(B, S_j|D_i)]P(D_i)}$$

Next, we assume the $P(D_1) = P(D_2) = \cdots = P(D_n)$. The breach probability of flood defences can be obtained by

$$P(D_i|B) = \frac{\sum_j P\left(B, S_j\middle|D_i\right)}{\sum_i \sum_j P\left(B, S_j|D_i\right)} \tag{5.4}$$

After we calculate the breach probability for each flood defence, the probability of at least one defence breach can be obtained as

$$P_{breach} = 1 - [(1 - P_F) * (1 - P_G) * (1 - P_H) * (1 - P_I) * \left(1 - P_J\right)] \tag{5.5}$$

5.4.3 Flood resilience bond payoff specification

As the methodology showed in Chapter 3, the flood resilience bond will be assumed as a zero-coupon bond. The valuation framework follows Eq. (3.1) to define the two components, dynamic interest and dynamic losses.

In accordance with Eq. (3.8), the dynamic loss is represented by the distribution from historical data. The distribution of flood dynamic losses in Towyn then becomes the combination of losses from different surges, where

$$P_{L_T} = (P_{L_{4m}} * P_{4m} + P_{L_{5m}} * P_{5m} + P_{L_{6m}} * P_{6m}) * P_{breach} \tag{5.6}$$

In this way, according to Zimbidis et al. (2007) and Shao et al. (2015), the value of the bond can be expressed in a piecewise function under different conditions. The simulated flood dynamic losses have been tested using three-levels of surges; therefore, the final valuation framework of flood resilience bond can also be expressed as a piecewise function

$$V_t(R_t, S, D) = \begin{cases} B_{CIR}(t,T) * \rho F \ or \ F * \ P_{L_{4m}} & S \in (\mu_3, \mu_4], with \ L_{4M} - \text{ǯ} L_{4m}[> D]or[\leq D] \\ B_{CIR}(t,T) * \rho F \ or \ F * \ P_{L_{5m}} & S \in (\mu_4, \mu_5], with \ L_{5M} - \text{ǯ} L_{5m}[> D]or[\leq D] \\ B_{CIR}(t,T) * \rho F \ or \ F * \ P_{L_{6m}} & S \in (\mu_5, \mu_6], with \ L_{6M} - \text{ǯ} L_{6m}[> D]or[\leq D] \end{cases} \quad (5.7)$$

where

V_t – is value of the flood resilience bond at time *t*;

R_t – is dynamic interest rate with an application of CIR model;

S – is surge height, where 3 < S < 7;

D – represents trigger value; the trigger value is set within the range: low boundary as $mean\ (L_{4-6m}) * P_{4-6m}$ and high boundary as $max\ (L_{4-6m}) * P_{4-6m}$;

ρ – is the proportion of the face value repaid to investors if bond triggered;

F – is face value of resilience bond;

$P_{L_{4m-6m}}$ – is the probability of dynamic losses generated from different levels of surges;

ǯ – is resilience impact from flood defence resilient project, where $0 < \text{ǯ} < 1$.

5.5 Data and results discussion

The probability distribution of the economic losses data from the 1990 flood events in Towyn shows a thinner tail than the exponential distribution. Therefore, we use three tests: Kolmogorov Smirnov, Anderson Darling, and Chi-Squared, to measure the fitness of the database; Table 5-1 presents the ranking of the fitness test for different distributions with different surge levels.

Table 5-1 Distribution fitness tests

Surge Level	Distributions / Tests	Kolmogorov Smirnov	Anderson Darling	Chi-Squared
4 metres	GEV	0.222	1.2863	1.5086
	Normal	0.34338	3.6219	1.1773

	Lognormal	0.33616	4.0887	0.22018
	Weibull	0.32209	3.6727	0.46816
5 metres	GEV	0.11914	7.8505	N/A
	Normal	0.294	3.7763	11.62
	Lognormal	0.35885	5.0038	2.6767
	Weibull	0.33049	4.5405	0.37505
6 metres	GEV	0.12766	0.55678	0.1787
	Normal	0.24911	1.7497	4.1259
	Lognormal	0.26659	2.6924	7.4065
	Weibull	0.27207	2.4088	5.1501

The comprehensive results from the tests indicate that the generalised extreme value distribution is more suitable for describing the simulated data; thus, the GEV distribution is selected to define the trend of economic losses from the three-level surges. Based on the practical records, the variable factors of the three surge levels are given in Table 5-2.

Table 5-2 Probability of surge levels

Surge level (m)	**Return period**	**Probability of occurrence**
4.0	< 20 years	0.9512261
5.0	20 years to 75 years	0.0355289
6.0	> 75 years	0.0132451

The five flood defences are the most essential flood defences covering part of the town in the land below 3- to 5-metres of elevation. Thus, the breach probabilities of flood defences F, G, H, I and J are presented in Table 5-3.

Table 5-3 Probability of breach for flood defences

Defence	F	G	H	I	J
Breach probability	0.370879	0.027855	0.019714	0.333368	0.246095

By computing the probability of the breach for each flood defence, the probability of at least one flood defence breach can be computed using formula (5.5), where

$$P_{breach} = 1 - [(1 - 0.370879) * (1 - 0.027855) * (1 - 0.019714) * (1 - 0.333368) * (1 - 0.246095)] = 0.6987.$$

To define the distribution of post-flooding economic losses, (X_j), the data generated from the three different surge heights have been fitted into several related distributions, e.g., Weibull distribution, Normal distribution, Generalised Extreme Value distribution, and Lognormal distribution. These distributions are tested by Kolmogorov Smirnov, Anderson Darling, and Chi-Squared. The results show that the Generalised Extreme Value distribution is the most appropriate distribution for describing the trend of post-flooding economic losses data. According to Stevens et al. (2016), 785 national flooding events have been recorded in the UK during the past 100 years. The database shows that reported flooding events significantly increase during the 20th/21st centuries. Therefore, we assume that the frequency, (N_t), is followed by the homogenous Poisson process (HPP) and the intensity, (λ), is 7.85, and the surges are followed the Poisson process with independent occurrence probability. The dynamic interest rate is generated using the parameters for the CIR model from (Nowak and Romaniuk 2013). In Table 5-4 we can observe the parameters used for pricing the resilience bond. Based on the face value of 100 for the bond, we can compute the prices of the resilience bond, assuming a resilient project that has provided 50% of resilience to the whole system.

Table 5-4 Parameters of flood resilience bond pricing model

	Parameter set A
Cox-Ingersoll-Ross model	a = 0.0241, b = 0.0539, σ = 0.0141, r_0 = 0.0614
Intensity under HPP	$\lambda = 7.85$
4m surge GEV distribution	k = -1.15308, σ = 3.31024e+05, μ = 2.03156e+06
5m surge GEV distribution	k = -1.10344, σ = 1.17273e+06, μ = 7.40161e+06
6m surge GEV distribution	k = -1.16737, σ = 1.40609e+07, μ = 4.03551e+07
Trigger range	[8,000,000 to 28,000,000]

Figure 5-3 and Table 5-5 show the prices of the flood resilience bond under 50% resilience. The price of a five-year flood resilience bond and catastrophe bond for Towyn varies under different thresholds and times.

Figure 5-3 Price of resilience bond for Towyn with 50% resilience effect under GEV distribution

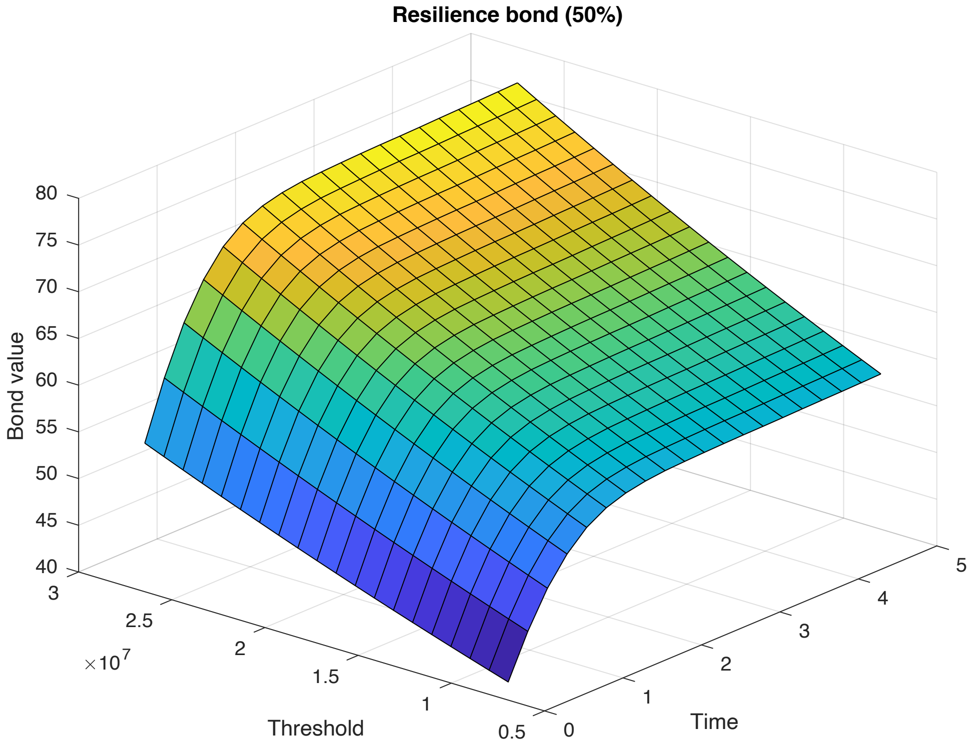


Table 5-5 Price of flood resilience bond with 50% effects under different thresholds

Period/Triggers	≈8 million	≈14 million	≈20 million	≈28 million
Year 1	42.39	58.06	59.03	59.38
Year 2	45.14	61.82	62.86	63.23
Year 3	48.06	65.81	66.91	67.31
Year 4	51.14	70.03	71.20	71.63
Year 5	54.39	74.49	75.74	76.18

We find that the prices of the bond approach the face value as the maturity period gets closer. The price of the flood resilience bond under the highest threshold of 28 million is 76.18 over the 100 face value of the bond. Whereas the price of a catastrophe bond under the same threshold is 74.19. The yield of the two bonds is calculated following Yield = $(\frac{Future\ Value}{Purchase\ Price})^{\frac{1}{n}} - 1$, (n = years to maturity), where the yield of resilience bond is 5.48% and yield of catastrophe bond is 6.15% for Towyn. If the pre-defined insurance contract sets the threshold at 14 million, then the yield of the resilience bond at year 5 maturity is 6.06%, and the yield of catastrophe bond is 15.63%. Hence, we consider the threshold as a significant influential factor in the pricing model, which will vary the price of the bond.

5.5.1 Sensitivity analysis

The process and results of a sensitivity analysis discussed here aim to provide suggestions and predictions for decision-makers regarding the price of the flood resilience bond in the market. The impacts of different input variables are tested to price the Towyn flood resilience bond. First, we know that resilient infrastructure projects deliver positive effects to the whole flood defence system; different resilience levels provided from the project are thus applied to compute the flood resilience bond price. Next, the losses data from the simulation are used to calibrate the distribution parameters which describe the future trends of losses; however, various selection of parameters may lead to different parameters and result in differences in the price of the bond. In response, we consider different options of distribution to define the severity of losses from catastrophic flooding in order to analyse the effects on the bond prices. Finally, we test the effects from different dynamic interest rate models and different parameters to predict the future interest rate and pricing of the bond under different types of dynamic interest rates.

The resilient flood defence projects have led to different influences on Towyn since resilience levels are likely to vary in response to different performances of the projects. To study how the resilience level will influence the prices of the flood resilience bond, we next test the resilience level at 10% and 90%. Figure 5-4 and Table 5-6 show the prices of the flood resilience bond under the 10% level. In this test we assume the resilient flood defence will improve 10% resilience to the whole flood system in Towyn.

Figure 5-4 Price of flood resilience bond for Towyn with 10% resilience

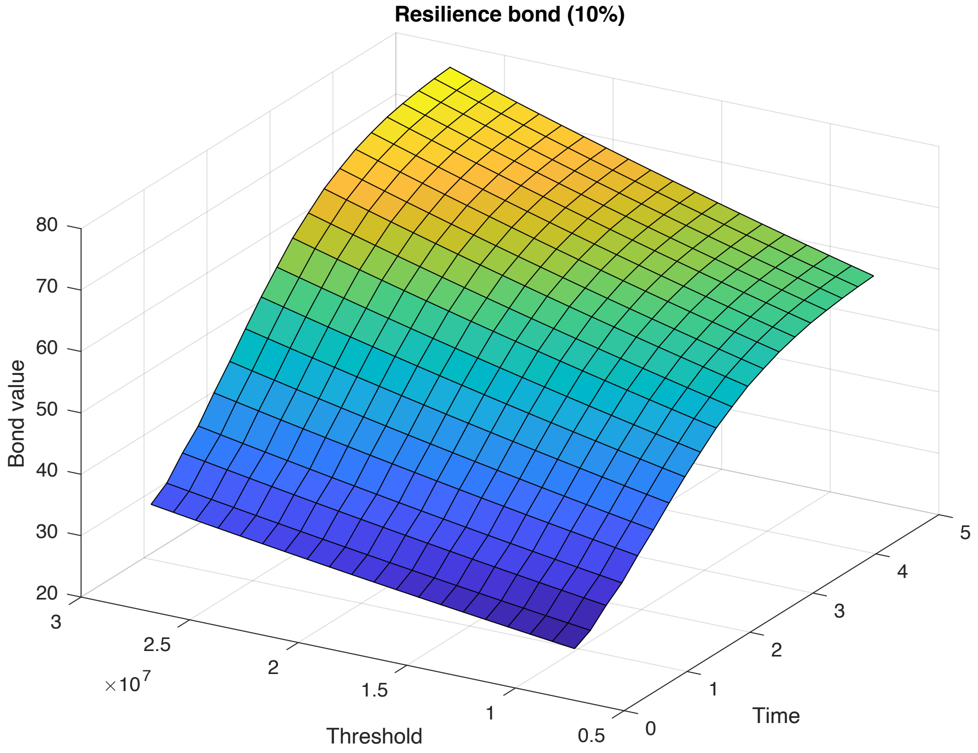


Table 5-6 Price of flood resilience bond (10%) under different thresholds

Period/Triggers	≈8 million	≈14 million	≈20 million	≈28 million
Year 1	27.56	42.40	55.28	59.42
Year 2	29.35	45.14	58.86	63.27
Year 3	31.24	48.05	62.66	67.35
Year 4	33.24	51.13	66.67	71.66
Year 5	35.35	54.38	70.90	76.21

Thereafter we assume the performance of the resilient flood defence project can provide 90% of resilience to the whole flood defences system, which is normally an impossible goal in practical terms. Nonetheless, we adopt this extreme value so as to calculate bond prices and analyse the movement of the prices based on different levels of resilience. The prices of flood resilience bonds under 90% resilience are given in Figure 5-5 and Table 5-7.

Figure 5-5 Price of resilience bond for Towyn with 90% resilience

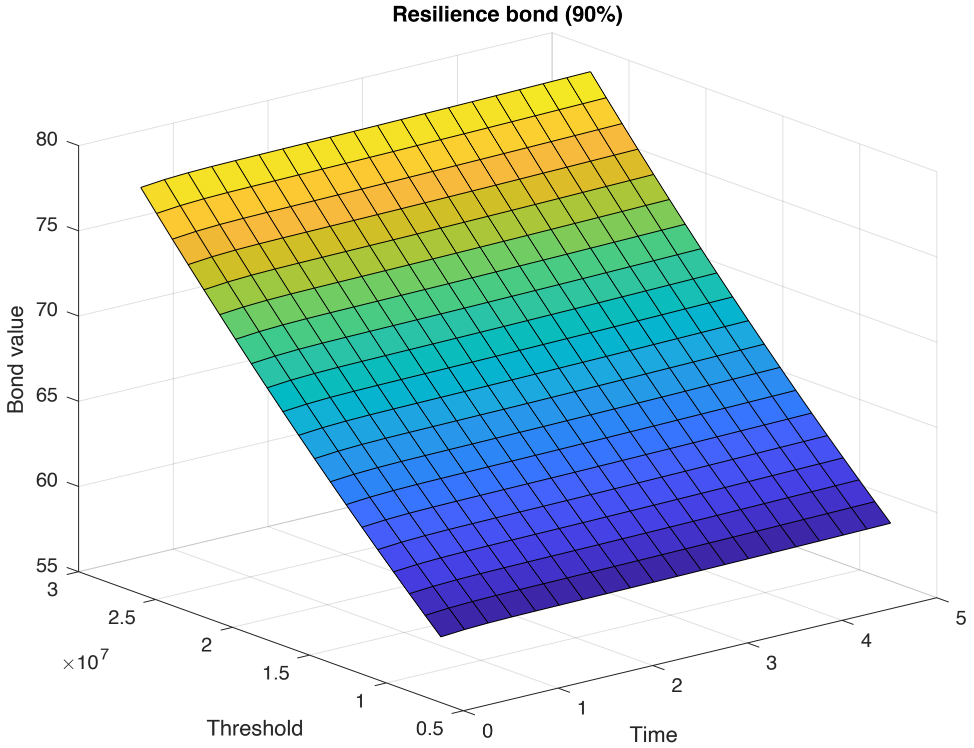


Table 5-7 Price of flood resilience bond (90%) under different thresholds

Period/Triggers	≈8 million	≈14 million	≈20 million	≈28 million
Year 1	60.84	61.05	61.11	61.23
Year 2	64.78	65.01	65.08	65.20
Year 3	68.95	69.20	69.27	69.40
Year 4	73.36	73.62	73.70	73.84
Year 5	78.03	78.30	78.38	78.53

Along with the increase in the resilience level, the price of the flood resilience bond is increased. The price reaches its highest point at year 5 with the highest threshold. Conversely, the price of the bond in the lowest point, at initial period of year 0, has the lowest threshold. From the design of the resilient project, its efficacy may directly influence the risks and losses reduced in the entire system. Consequently, a higher resilience level from the project will lead investors to pay the higher price, which means the investor will receive less coupon payment at the maturity of the bond since a higher resilience level of the project will reduce the risks of the bond being triggered.

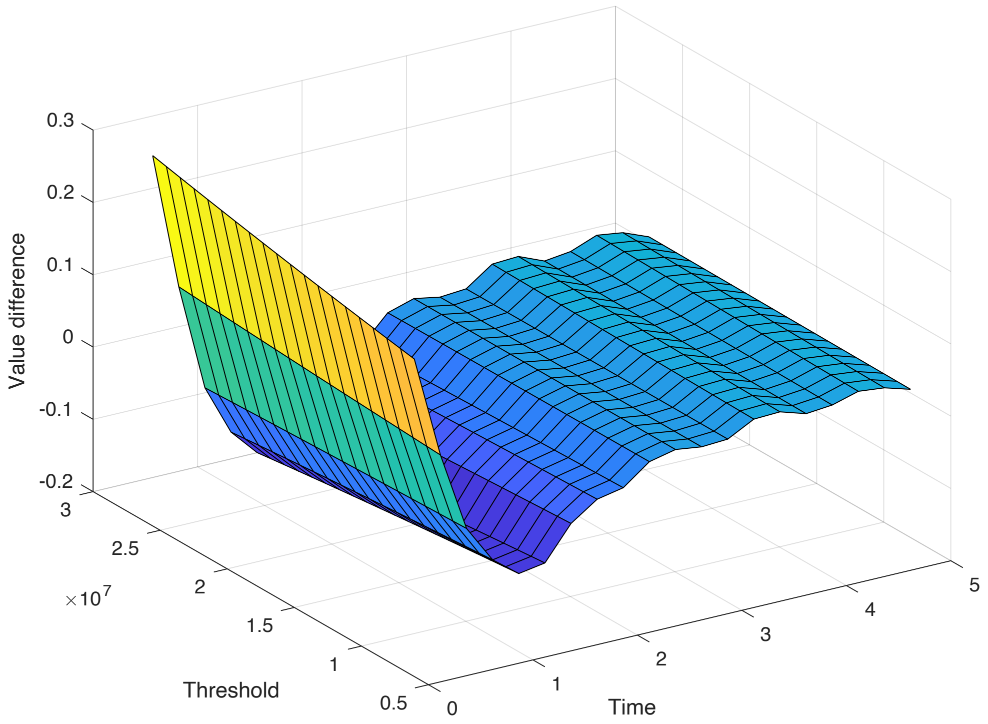
To accurately describe the economic losses dataset and forecast the future trend, we select the suitable distribution to fit the simulated data and calibrate the parameters used to generate random numbers to simulate future economic losses. Hence, we switch the dataset of economic losses from different surge levels to lognormal distribution, which is normally applied to define the tailed data set and generate stochastic expected losses. We calculate the flood resilience bond by applying the parameters in Table 5-8.

Table 5-8 Losses from flood surges described by Lognormal distribution

	Parameter set B
Cox-Ingersoll-Ross model	a = 0.0241, b = 0.0539, σ = 0.0141, r_0 = 0.0614
Intensity under HPP	$\lambda = 7.85$
4m surge Lognormal distribution	μ = 14.4681, σ = 0.295991,
5m surge Lognormal distribution	μ = 15.7625, σ = 0.291758,
6m surge Lognormal distribution	μ = 17.4475, σ = 0.437827,
Trigger range	[8,000,000 to 28,000,000]

Table 5-8 displays the parameters using the Lognormal distribution. Next, the value difference of Towyn flood resilience bond between the use of the distribution of GEV and Lognormal is shown in Fig. 5-6. In the statistical analysis of the prices, the expected losses from the simulated data are used to calibrate the suitable distribution, which will describe the expected exposure of the assets to future catastrophic flooding over a given time range. We notice that the value difference for the Towyn flood resilience bond between the two distributions is in the range [-0.2 to 0.3]; this result shows that GEV distribution is more appropriate for describing the future trend of catastrophic losses. Whereas lognormal distribution has overestimated the price; therefore, consideration of the distribution goodness of fit for the dataset may result in inaccurate prices for bonds. The value in the initial period shows a significant difference, but the inaccurate value situation will reduce along with the increase of transactions and maturity period. Also, from the observation we notice that the value difference is smaller in the low threshold than in the high threshold. We consider the distribution goodness of fit to be an essential impact factor of the pricing model since, by switching distributions and the pre-defined threshold, the significant change of bond value may cause prices to vary too.

Figure 5-6 Value difference by applying GEV and Lognormal distribution



The present analysis considers in detail the influence of dynamic interest rate by switching the interest rate model and parameters to test the sensitivity of bond prices. Shao (2015) states that the dataset period of interest rate is not necessary to match the insurance loss data because the catastrophe risks are independent of financial risks. Therefore, we apply the 12-month LIBOR historical rate from 2000 to 2011 to calibrate the parameters and generate the stochastic interest rate. Thereafter, we obtain the value differences under different interest rate models and interest rate parameters using the parameters shown in Table 5-9.

Table 5-9 Parameters of flood resilience bond under different interest rate models

	Parameter set C
Vasicek model	a = 0.212, b = 1.085, σ = 0.4208, r_0 = 0.011
Cox-Ingersoll-Ross model	a = 0.212, b = 1.085, σ = 0.4208, r_0 = 0.011
Intensity under HPP	$\lambda = 7.85$
4m surge GEV distribution	k = -1.15308, σ = 3.31024e+05, μ = 2.03156e+06
5m surge GEV distribution	k = -1.10344, σ = 1.17273e+06, μ = 7.40161e+06

6m surge GEV distribution	k = -1.16737, σ = 1.40609e+07, μ = 4.03551e+07
Trigger range	[8,000,000 to 28,000,000]

Table 5-9 provides the parameters using the different interest rates. In subsequent figures, the price of the flood resilience bond is calculated using different models and parameters to generate various dynamic interest rates. We begin with the price of the resilience bond value differences shown in Fig. 5-7.

Figure 5-7 Price of resilience bond for Towyn, Wales with 50% resilience effect under CIR model with different parameters

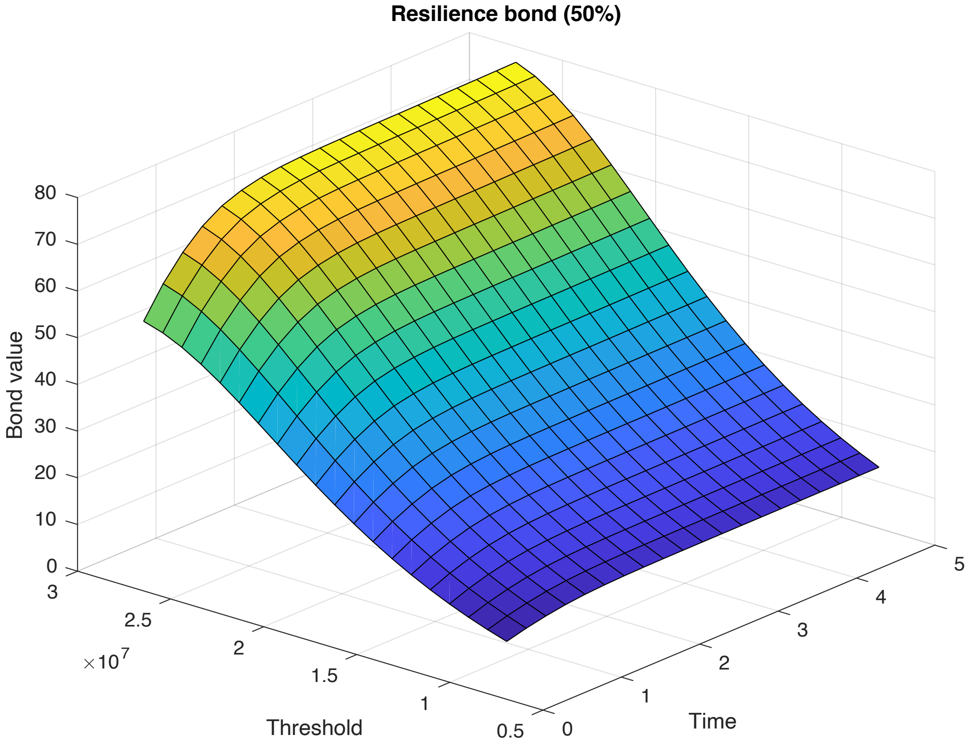


Table 5-10 Price of resilience bond for Towyn with 50% resilience effect under CIR model with different parameters

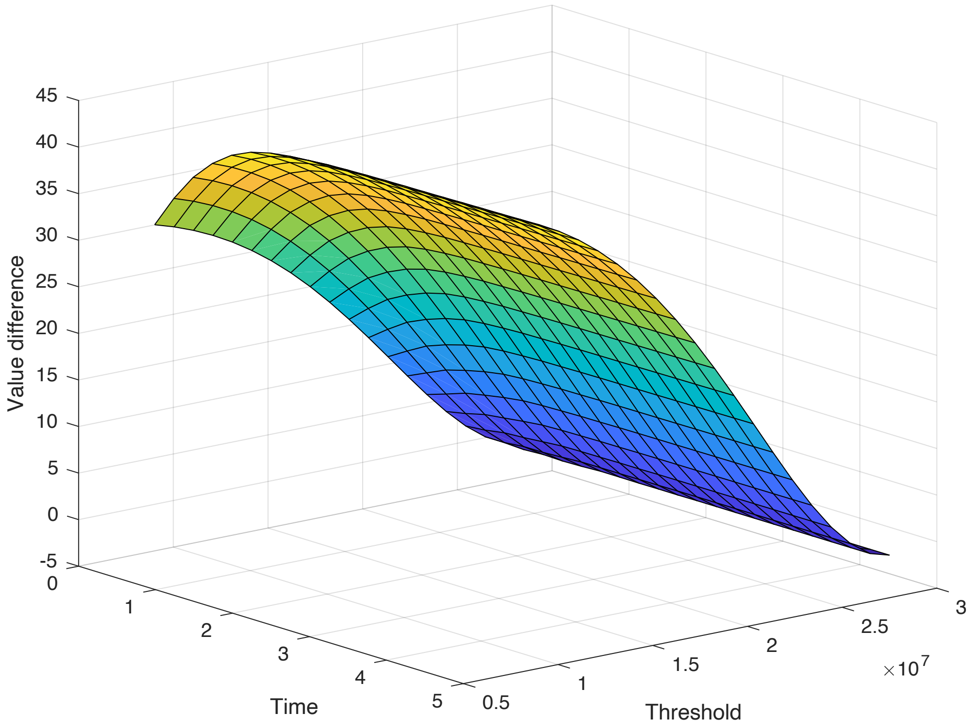
Period/Triggers	≈8 million	≈14 million	≈20 million	≈28 million
Year 1	13.71	18.79	19.11	19.23
Year 2	22.15	30.35	30.87	31.05
Year 3	33.69	46.18	46.96	47.24

Year 4	46.37	63.55	64.63	65.02
Year 5	54.64	74.89	76.16	76.61

Figure 5-7 and Table 5-10 show the prices of resilience bond by using 50% resilience under the CIR interest rate model.

In Fig. 5-8, the value difference is in the range of [-5 to 45], where the differences are decreasing in conjunction with the raising of threshold and time. By switching the parameters in the CIR model, we observe that the jump diffusions of the dynamic interest rate generated from the stochastic model are diverse. Results obtained from the changes in the CIR model lead to big differences in prices of the flood resilience bond. In the next step, we evaluate different interest rate models in the pricing model to test the influence of switching the CIR interest rate model to the Vasicek interest rate model.

Figure 5-8 Value difference between different CIR model parameters



By using the same parameter with a different model, the price of the bond is obtained, as shown in Fig. 5-9.

Figure 5-9 Price of resilience bond under Vasicek interest rate model

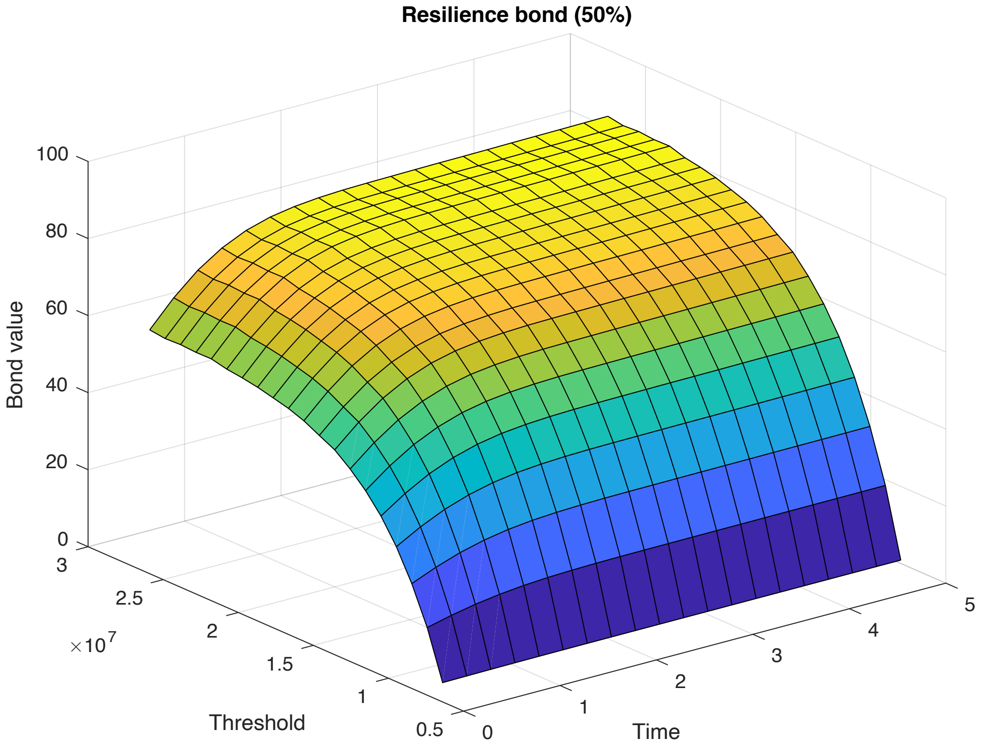
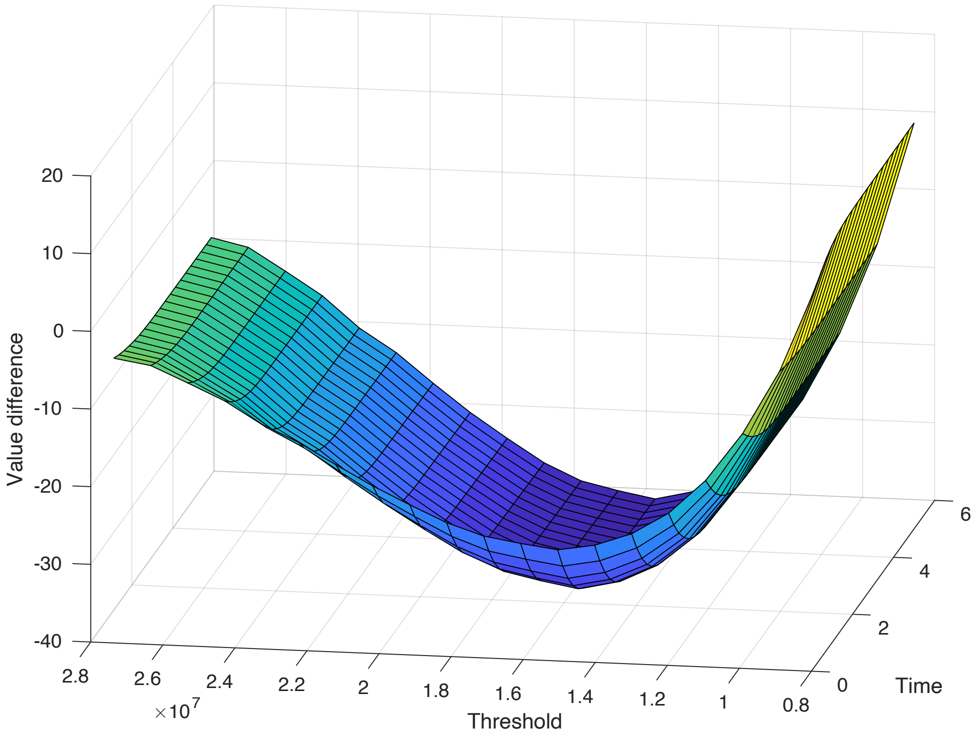


Figure 5-10 shows the value difference between the Vasicek model and the CIR model. The Cox-Ingersoll-Ross (CIR) model improves the disadvantage of the Vasicek model, in that it avoids the occurrence of negative interest rate. In the results of value difference, we notice that the bond price is higher when applying the Vasicek model than the CIR model. When we compare the Vasicek to the CIR model, Vasicek will lead to an overestimate of bond prices in the market. However, the significant differences are reducing along with the increase of the threshold level. Main results indicate that zero-coupon bond prices are sensitive to the fluctuations of dynamic interest rates.

Figure 5-10 Value difference between applying Vasicek and CIR model



5.6 Conclusion

This chapter has focused on the design and modelling of flood resilience bonds applied to Towyn, North Wales as a case study. We have developed a model to value the bond, which was used to hedge the flood risks and support the resilient flood defence projects with its unique functions. A practical case study with simulation techniques was used in Towyn to obtain the data used in the development of the pricing model. Several research conclusions are noteworthy.

The design of the flood resilience bond may offer a good opportunity to attract more capital market investors. The structure of the resilience bond may connect the capital market and insurance market, meanwhile generating more opportunities for efficient public-private partnerships for future investments in resilient infrastructure projects. From our simulations, we have noticed that the breach of different flood defences may indeed lead to unexpected losses for the town; flood defence enhancement projects are urgently needed to improve the resilience of the existing flood defence system and protect local coastal residents. Modeling the expected losses from breaches using resilience enhancement projects indeed provides essential information to coastal decision makers about the opportunity cost of the long-term financial advantages of preparing in advance.

In our pricing model for a five-year flood resilience bond for Towyn we compared catastrophe bonds to resilience bond prices under the highest threshold of approximately 28 million and calculated that a 50% resilience from a resilient project will generate a 0.67% reduction in the returns by switching from CAT bond to resilience bond. We verified that risks associated with a resilience bond are lower than the catastrophe bond and the resilience bond offers additional returns for investment. However, since the threshold is considered as one of the significant influential factors to the price and yield for both bonds, the yield of resilience bond is 6.06% and the yield of catastrophe bond is 15.63% under the threshold of about 14 million. In this situation, a 50% resilience effect from the resilient project will generate a 6.75% difference in the returns as the benefit of switching from catastrophe bond investment to resilience bond investment.

From the sensitivity analysis, we found that threshold, dynamic interest rate, and performance of resilient projects are the main influential factors upon prices of the flood resilience bond. A higher resilience level provided from the resilient project will increase the price of the bond and lead to lower returns for bond investors, due to the fact that the risk of losing the principal has been reduced. In addition, from the test of different interest rate models, the flood resilience bond shows that the price will rise along with the increasing of trading time, because fewer occurrences of trigger events during longer trading periods will lower the probability of economic losses and reduce the risks. As the results from comparisons in Figs. 5-6, 5-8 and 5-10 indicate, the sensitivity test shows that the CIR model is the most centred interest rate model; it provides more accurate prices than Vasicek model since the setting of $\sqrt{r_t}$ has avoided the occurrence of negative interest rate value. Moreover, from the comparison of GEV and Lognormal distribution, the result proves that GEV is a more accurate way to represent the distribution of the economic losses from flooding events.

Chapter 6 UKRI GCRF Project - Multi-Hazard Urban Disaster Risk Transitions Hub - Earthquake Municipal Resilience Bond: A Case Study of Istanbul

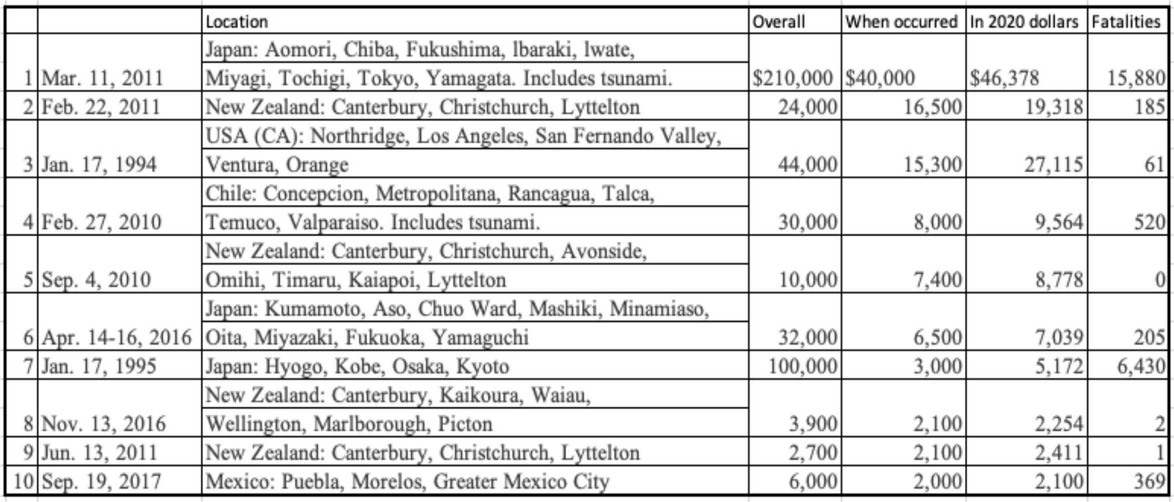
6.1 Introduction

The study is dedicated to the project of Tomorrow's Cities Istanbul Hub, which primarily focuses on the financing of resilient projects while working with policymakers through a close partnership with the Istanbul Metropolitan Municipality. "Tomorrow's Cities" is the UK research and Innovation (UKRI) Global Challenges Research Fund (GCRF) Urban Disaster Risk Hub. The project aims to catalyse the transition to crisis management, multi-hazard risk decision-making and informed planning for cities in low and middle-income countries. This chapter outlines the development of the Municipal resilience bond concept with the Istanbul Metropolitan Municipality since September 2020. As a high yield and short maturity bond, resilience bonds are attractive to key political actors in Turkey; the bond's unique function allows funds to be raised towards implementing resilient projects such as retrofitting and renewal. In this way, the concept of applying a resilience bond for Istanbul is not to reduce existing risks, but rather to the systematic reduction of risk in future developments.

As the largest and most populous city in Europe, Istanbul is recognised as Turkey's financial, commercial, cultural, and educational centre. However, Istanbul is situated on major active fault lines, making the city a significant earthquake zone and one of the most earthquake-prone cities in the world (Ay and Demires Ozkul 2021; Üstün 2016). According to Tekeli‐Yeşil et al. (2010), nearly 300 destructive seismic events were recorded in the world in the last decade, 21 of which occurred in Turkey, resulting in 18,234 deaths and $21,230 million in economic losses. The city of Istanbul is highly vulnerable, as it holds about one-eighth of the total population and houses 40% of Turkey's industrial facilities. Research from Ilkisik et al. (2010) shows that both Istanbul Metropolitan Municipality (IMM) and Japan International Cooperation Agency (JICA) have estimated that around 50,000 lives lost and approximately $65 billion in economic losses would be the outcome of a major earthquake (Mw = 7.4) near to Istanbul. The total number of predicted injuries could reach 150,000 and 650 hospitals are required for the recovery. However, 30% of the essential hospitals are located in the risky areas of the city. Erdik et al. (2003) have demonstrated that issues such as excessive urbanisation rate, faulty land usage and construction planning, lack of infrastructures and services, and environmental degradation have made Istanbul more susceptible to earthquake disasters. In response, Erdik and Durukal (2008) suggest three ways to prepare Istanbul and mitigate the risks from earthquakes: planning the buildings properly to avoid raising the existing risks, enhancing the existing buildings to reduce the risks, and applying insurance to transfer the risks. However, such mitigation and preparation projects put a heavy financial burden on local authorities in Istanbul.

Table 6-1 lists the top 10 costliest insured losses from earthquakes and tsunamis between 1980 and 2020. As per Kamiya and Zhang (2016), local government access to revenue is the key determinant for a city to provide mitigation and preparedness of infrastructure projects against catastrophes. However, when low public funds hinder city development, the need for private sector investment in infrastructure projects takes precedence (Koppenjan and Enserink 2009). García-Lamarca and Ullström (2020) argue that the lack of upfront investment funds put bonds “front and centre” in an essential long-term role as a debt instrument to raise capital. A Resilience Bond for Istanbul is therefore a novel and practical way to promote resilience, as the bond pricing is based on the expected improvement in resilience that can be achieved through project implementation.

Table 6-1 Top 10 costliest world earthquakes and tsunamis by insured losses, 1980-2020



		Location	Overall	When occurred	In 2020 dollars	Fatalities
1	Mar. 11, 2011	Japan: Aomori, Chiba, Fukushima, Ibaraki, Iwate, Miyagi, Tochigi, Tokyo, Yamagata. Includes tsunami.	$210,000	$40,000	$46,378	15,880
2	Feb. 22, 2011	New Zealand: Canterbury, Christchurch, Lyttelton	24,000	16,500	19,318	185
3	Jan. 17, 1994	USA (CA): Northridge, Los Angeles, San Fernando Valley, Ventura, Orange	44,000	15,300	27,115	61
4	Feb. 27, 2010	Chile: Concepcion, Metropolitana, Rancagua, Talca, Temuco, Valparaiso. Includes tsunami.	30,000	8,000	9,564	520
5	Sep. 4, 2010	New Zealand: Canterbury, Christchurch, Avonside, Omihi, Timaru, Kaiapoi, Lyttelton	10,000	7,400	8,778	0
6	Apr. 14-16, 2016	Japan: Kumamoto, Aso, Chuo Ward, Mashiki, Minamiaso, Oita, Miyazaki, Fukuoka, Yamaguchi	32,000	6,500	7,039	205
7	Jan. 17, 1995	Japan: Hyogo, Kobe, Osaka, Kyoto	100,000	3,000	5,172	6,430
8	Nov. 13, 2016	New Zealand: Canterbury, Kaikoura, Waiau, Wellington, Marlborough, Picton	3,900	2,100	2,254	2
9	Jun. 13, 2011	New Zealand: Canterbury, Christchurch, Lyttelton	2,700	2,100	2,411	1
10	Sep. 19, 2017	Mexico: Puebla, Morelos, Greater Mexico City	6,000	2,000	2,100	369

Source: (Insurance-Information-Institute 2020).

This chapter consists of three parts. The next section reviews financial instruments integrated with earthquake risk assessment and mitigation. After that, we consider the resilient infrastructure projects by taking Istanbul as our case study. Lastly, we propose a conceptual model of the Istanbul Municipal resilience bond.

6.2 Financial instruments integrated with earthquakes: Turkey

Unexpected earthquake events have caused unpredictable and devastating impacts on societies, and the historical lessons learned from earthquake catastrophes demonstrate that engineers should take responsibility for the design and construction of infrastructure. In this way, infrastructures in earthquake-prone areas can meet the requirements to hedge unforeseen earthquake strikes; for example, the key infrastructures of government buildings, airports, roads, harbors, and hospitals are expected to remain continuously functional when earthquakes occur (Dobie 2011). According to Linnerooth-Bayer and Hochrainer-Stigler (2015), two advantages – mitigation of losses and damages, and reduction of the societal burden by avoiding moral hazards – can be realised from well-designed financial instruments. Therefore, in the following sections we discuss how the efficient management of the financial instruments integrated with earthquake events may diversify investors from different sectors, reduce the cost of funding, and close the investment gap in regions.

Insurance and reinsurance can enhance the ability of countries struck by earthquakes to receive guaranteed repayment for economic losses and reconstruction. Research from Tao and Tao (2005) concludes that (re)insurance has been deemed as the most effective and equitable tool to hedge an earthquake catastrophe, given that applying insurance services is the main method in the market. Conventionally, insurance companies will accumulate earthquake risks by providing insurance services to individuals, and then redistribute the risks to bigger reinsurance companies. The standard earthquake insurance will take deductibles in the percentage (2%-20%) to the replacement value of structures instead of the amount of cash where the percentage of the deductible depends on the risk of earthquake (Insurance-Information-Institute 2020). For instance, the consumer with a 2% deductible policy would need to be responsible for a $2,000 initial cost if the rebuild cost of a house is $100,000. Moreover, in some insurance companies, consumers may also receive a discount on insurance premiums if they take a high voluntary deductible percentage.

As part of the diversification strategy for earthquake events, earthquake coverage is different in other countries. According to Athavale and Avila (2011), significant magnitude earthquakes potentially cause widespread economic chaos, injury and deaths in countries where earthquakes have recently occurred, as in Turkey, China, Haiti, Chile, and New Zealand; therefore, as a low-probability but high-consequence losses coverage policy, earthquake insurance is not mandatory in standard homeowner's insurance in some countries, but is instead purchased separately as an additional policy. A report from the OECD (2018) shows that 50% of the 34 researched countries have an automatic extension of earthquake insurance, and 24 countries set earthquake insurance as an optional add-on policy based on residential/commercial property policies. Countries such as Albania, Costa Rica, Papua New Guinea, Peru, Serbia, Switzerland, and Turkey have both types of earthquake insurance services. Research by the OECD (2018) indicates that providers of insurance to cover earthquakes in many countries are private insurance companies that include both OECD and non-OECD countries, such as Australia, Canada, Italy, Mexico, Greece, Germany, Peru, etc. Private insurance companies are also major providers of coverage for the secondary perils of fire and tsunami in some countries. As Le Pan (2016) states, the insurance policies at regional and national levels may not be suitable for following the law of large numbers, since the risks of an earthquake at these levels are highly concentrated and geographically clustered. Whereas sustainable business and financial tools are increasingly expected to be available to local and national governments when they face higher costs from catastrophes and therefore must disperse benefits (Vaijhala and Rhodes 2018).

Given that earthquake damage can impose devastating impacts to households without earthquake insurance, governments have begun to realise the importance of earthquake insurance coverage. For example, Bommer et al. (2002) have shown how destruction from earthquakes has led to significant adverse implications for the Turkish government, since it is legally responsible for the recovery payments, especially after two high magnitude earthquakes in 1999. Earthquake insurance thus became compulsory in Turkey after 1999. However, Le Pan (2016) argues that Turkey government involvement in the insurance industry may lead to a disincentive for private insurers; such involvement has increased government responsibility in the co-insurance, which can be seen as a moral hazard issue. For instance, Yucemen (2005) explains that the legal obligation for the Turkish government to fund the costs of post-earthquake recovery has created an unplanned financial burden on the national economy and has restricted the existing budget for the preparation of earthquake catastrophes. Palm (1995) asserts that, despite public authority provision of temporary shelter, tax relief and loans from, e.g., the U.S. Federal Emergency Management Agency (FEMA) to earthquake victims for rebuilding, households without earthquake insurance will still have to repay the loans. Therefore, the Turkish government decided to privatise the risks by offering insurance via the Turkish Catastrophe Insurance Pool (TCIP) where risks are redistributed to global reinsurance(s) and the capital market (Bommer et al. 2002). However, Goda (2013) states that conventional financial risk management tools like public support and earthquake insurance show less efficiency in responding to recent catastrophes.

The inclusion of earthquake coverage has led to insolvency of insurance companies, huge national debt and stagnant local economies in countries worldwide. For example, the recent catastrophes in New Zealand and Japan have caused around $12 billion and $40 billion in insurance losses, respectively. Woo (2004) says that insurers may be facing financial stress that jeopardises their credit ratings after a sequence of two or more catastrophic events in a short period. Furthermore, the full coverage of insurance in the market may be expensive and difficult to obtain. As a result, the redistribution of unforeseen earthquake risks and the option of insurance-linked securities, e.g., the resilience bond, have gained more attention in the earthquake risk market. In response, and due to fewer available resources for urban renewal, the Istanbul Metropolitan Municipality has declared its interest in the application of a resilience bond in the project “Tomorrow’s Cities” as an effective option for integrating risk reduction into existing infrastructure project implementation frameworks.

6.3 Financing resilient infrastructure projects: a proof of concept of the municipal resilience bond in Istanbul

According to Fourie (2006), infrastructure can be broken into two categories, social and economic. Social infrastructure can be defined as ‘soft’ infrastructure in which investment aims to promote the marginal productivity of human capital such as schools and hospitals. Whereas economic infrastructure can be defined as ‘hard’ infrastructure in which investment achieves the goal of improving economic activities such as transportation and energy. As a subset of the infrastructure sector, social infrastructure is especially geared to social services and the development of hospitals, schools and universities, council housing, and emergency facilities for communities. The experimental results of Kara et al. (2016) demonstrate that investment from public capital to social infrastructures such as schools and hospitals will efficiently improve labour productivity and enhance regional output and input, the main factors for increasing regional income in Turkey. In a recent report by Saygılı and Özdemir (2021), the share of investment in infrastructure development in Turkey has increased from 56.6% to 65.6% between years 2007 and 2015. Also, 23% of the investment has been dedicated to social infrastructure development because investment in social facilities is expected to lead to an increase in human capital and improve social life. Serdaroglu (2020) emphasises the link between soft and hard infrastructure; an investment in the improvement of human capital and social infrastructure is equally significant as an investment in the physical (economic) infrastructure because an investment in social infrastructure is the necessary condition to ensure the effectiveness and benefit of physical infrastructure. As per Melikoglu (2013), based on Turkey Vision 2023, the Turkish government is planning to prioritise infrastructure investments in support of economic productivity over the medium and long term. Since investment in social infrastructures is receiving attention in Turkey, the available data from the Turkish Statistical Institute show that Istanbul is becoming one of the highest per capita income cities in the western regions of Turkey. In Turkey Vision 2023, Istanbul is involved in several "Megaprojects"; for example, the third airport in Istanbul is under construction and is one of the largest in the world in terms of passenger capacity. Canal Istanbul, an artificial sea-level waterway, will be built to connect the sea of Marmara to the Black Sea (Investment-office 2015). The boom of Istanbul's infrastructure is caused by rapid urban development in Turkey, and one aim of Vision 2023 is to build Istanbul as one of the top 10 financial centres in the world. However, Herr (2017) shows that, although Istanbul is one of the megacities in the world spanning both Asia and Europe, with over 14 million residents, water and wastewater management and urban transport are nevertheless urgent issues needing to be solved by local government. Moreover, Istanbul as one of the over-agglomerate megacities (Kaya and Koc 2019; Kötter and Friesecke 2009; Nilsson et al. 2014), and due to resource scarcity, is in dire need of expansion of its infrastructures in transport, education and healthcare under a sustainable development framework; otherwise, uncontrollable increases in population in megacities are likely to lead to lower overall life quality for societies due to congestion and pollution.

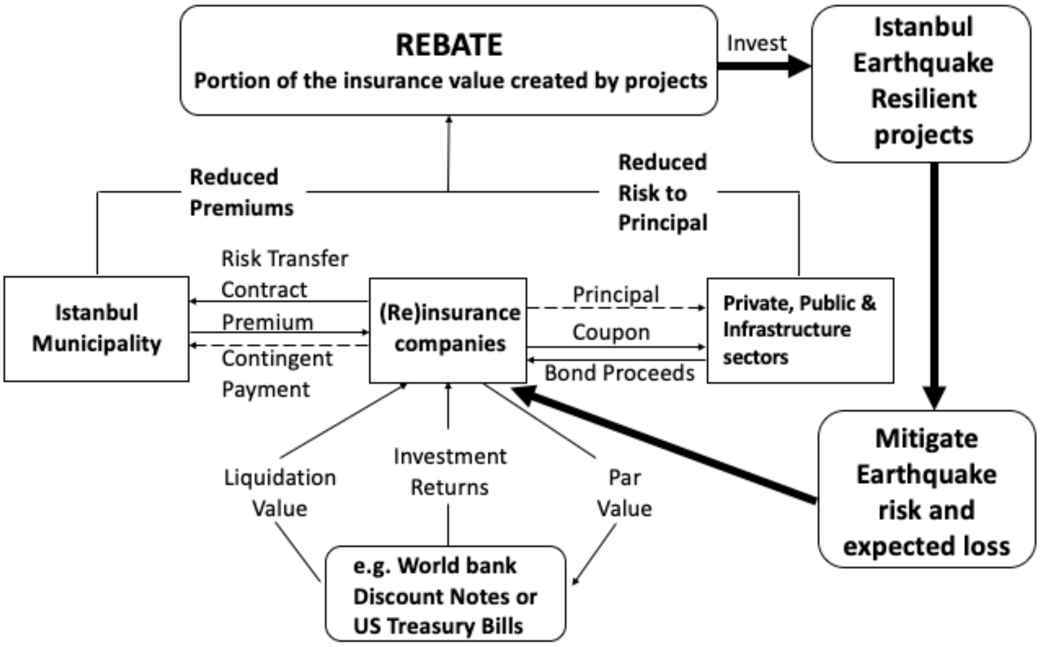
Well-designed infrastructure investment will generate economic benefits in countries over the long term; in the meantime, it will increase the potential for economic growth and productivity as well as bring significant positive spill-over effects to economies like Turkey (Serdaroğlu 2016). Along with the increase in Turkey's population, the development of infrastructures in megacities like Istanbul calls for significant investment from the public sector in areas such as freshwater and wastewater management, traffic, and public transport (Herr 2017). As per the OECD (2015b), the aim of global infrastructure investment in transport, water, transmission, distribution, and telecommunications is USD 71 trillion from 2007 to 2030, which amounts to 3.5% of annual world GDP. Furthermore, around 85% of annual world GDP will need to be invested in global infrastructure between 2013-2030 to fulfil the needs of growing populations. However, only 34% of the investment has been dedicated thus far to the development of the infrastructure sector. In this context, Göymen (2000) also discusses how the Turkish government has gradually shifted from purely basic state-sponsored and managed development to the PPP (Public-private partnership) model since the 1980s. Moreover, as one of the alternatives in the PPP model, Municipal bonds are demonstrating their advantages as financial tools when financing infrastructures in emerging economies (Leigland and Thomas 1999).

6.3.1 Developing the municipal resilience bond market in Istanbul

Istanbul is a megacity vulnerable to large earthquakes, with a 2% probability of annual occurrence. Durukal et al. (2006) also point out that only 30% of approximately 800,000 buildings in Istanbul have earthquake insurance as of 2006. According to Görmez et al. (2011), the Metropolitan Municipality of Istanbul has been involved in ongoing efforts to prepare facilities with relief aid in advance and implement post-catastrophe response operations, because a mega-destructive earthquake is forecast to occur relatively soon. Other decisions have been made by the Turkish government and businesses to strengthen urban resilience and expand insurance coverage. For example, the Turkish Catastrophe Insurance Pool has issued a second catastrophe bond (SwissRe 2018a). As the proof of concept to apply resilience bond for Istanbul in the project, there are examples of noteworthy best practices. Üstün (2016) suggests that Istanbul administrations could study and adapt good disaster resilience management by allocating financial resources efficiently, upgrading and retrofitting infrastructures and buildings, and updating infrastructure and public facility damage status information.

As Istanbul Metropolitan Municipality (IMM) mentioned in the support letter for the project Tomorrow's Cities, financial tools are invaluable for IMM's work on the urban redevelopment and retrofitting projects for providing a financial solution in line with the engineering aspects. This research theme is especially vital for the urban poor who are mostly dependent on supplementary economic support in order to take part in such urban projects. Whereas a municipal resilience bond could potentially be the key for the Istanbul municipality to raise sufficient funds from capital market investors, especially for resilient infrastructure projects like redevelopment and retrofitting and acquiring insurance services to hedge potential economic losses from unpredictable earthquakes. Figure 6-1 schematises the mechanism for resilience bonds in the development of resilience in Istanbul by proposing the Municipality as the sponsor.

Figure 6-1 Istanbul Municipal Resilience Bond mechanism



Source: Adapted from RE bound insuring for Resilience Report 2015.

To understand how the municipal resilience bond can mitigate the financial consequences for asset owners and offer upfront investment funding for resilient infrastructures, it is imperative to review the functions of the resilience bond for the Istanbul Metropolitan Municipality. The insurance service is used to insure the sponsor to hedge unforeseen risks from catastrophes (Götze and Gürtler 2018). The report from Re:Focus (2015) describes how the sponsor of a resilience bond is normally the party interested in investing in resilient infrastructure projects to mitigate the physical risks from catastrophes and gain financial protection from insurance services. As the sponsor of the Municipal resilience bond, the IMM can hedge the economic losses and receive insurance protection by issuing the Municipal resilience bond via the issuer, e.g., insurance and reinsurance companies that transfer risks to the capital market (Polacek 2018). Consequently, collaboration is achieved by issuing a Municipal resilience bond between the IMM and insurance companies. In addition, Yamagata and Sharifi (2018) state that new infrastructures should not be built in risk-prone areas, and a retrofit project should be conducted to existing buildings and infrastructures to meet the requirements. An efficient resilient infrastructure project in Istanbul will reduce the risks to the city, and mitigated risks will then be quantified into values (rebates) by pre-defined risk modelling. A lower risk will bring a lower probability of triggering the bond repayment; hence, the reduced risks are quantified as the value reduction from the premium and coupon payment, which are then reinvested to support the resilient infrastructure project in Istanbul.

As the most populated city in Europe, Istanbul not only faces increasing pressure on its infrastructures (Istanbul 2018), but is also ranked number one in the assessment of potential economic losses from extreme weather events among 15 European coastal cities. Turkey experienced its extreme driest and extreme wettest weather in 2017, with severe rainfall and hail impacting heavily on the infrastructure sector, e.g., transport and housing. In response, the Istanbul Climate Change report recommended that adaptation actions and policies for Istanbul focus on mitigation of impacts from destructive catastrophes, e.g., increase investment in existing infrastructures, build new infrastructures more adaptive to the changing climate, and improve the preparedness of institutions and people. To build resilience in Istanbul is to improve how its infrastructures tolerate, cope with, absorb, and adjust to climate change threats. For instance, in addition to reducing fatalities and direct damage to buildings and infrastructures, earthquake engineering goals are to ensure the residual functionality and speed of recovery from earthquakes (Gernay et al. 2016).

Redevelopment and retrofitting projects are certainly eligible infrastructure projects where a Municipal resilience bond could be applied to reduce risks; the upfront investment fund could ensure that the project is completed and provide insurance service at the same time. In addition to hard infrastructures, Kundak (2017) asserts that individuals play essential roles in communities by having both available resources and the ability to manage those resources efficiently; therefore, social resilience is key to human capital at the community level. Adger

(2000) defines social resilience as, “the ability of communities to withstand external shocks to their social infrastructures.” As the number of residents in Istanbul grows, the need to improve the resilience of the social infrastructure will generate eligible infrastructure projects in the market, and thus expand opportunities to apply Municipal resilience bonds. Furthermore, Environmental, Social and Governance (ESG) investing is also gaining in popularity; ESG investors will examine the criteria within the environmental, social and governance categories in order to assess the performance of investments when using ESG metrics (Capelle-Blancard et al. 2016). According to Boffo and Patalano (2020), the application of ESG scoring and reporting may offer opportunities for companies to get involved in the management and resilience to create long-term value. The term ESG is normally interchangeable with Corporate Social Responsibility (SCR), in which corporations and investors consider the ESG criteria when taking management and portfolio decisions. Social Corporate Responsibility (SCR) is going mainstream in business activities; voluntary engagement in environmental protection and increasing workforce diversity and employee welfare are examples (Liang and Renneboog 2020). Studies by Hachenberg and Schiereck (2018) find that following the ESG approach improves the performance of financial instruments of companies better than financial instruments of companies without the ESG approach. Therefore, introducing the ESG evaluation into the Istanbul Municipal resilience bond may unlock the opportunity for the bond to be expanded in the ESG investment market. An ESG Municipal resilience bond enables the Istanbul Municipality to have access to more investors than other bonds and attract investors who are interested in ESG performance.

6.4 Conclusion

The chapter has been dedicated to the proof of concept of the Municipal resilience bond and the analysis of the mechanism of eligible projects in Istanbul. The Municipal resilience bond represents a great opportunity for Istanbul Metropolitan Municipality (IMM) to promote investment in enhancing resilience for the city, and also to prove that innovative financial mechanisms can be designed in support of resilience for the urban poor. The application of resilience bonds is attractive to the IMM because they allow capital to be raised towards implementation of an urban development/retrofitting/renewal project. As part of the design in the project “Tomorrow’s Cities”, building resilience to multi-hazards is based on two frameworks that have given rigorous consideration of hazard and vulnerability, as well as conducted an evaluation of the time value of money and risk: Combined earthquake retrofit plus insurance and upfront fund for infrastructure projects from Municipal resilience bond for new development and urbanisation areas. An application of the Municipal resilience bond can motivate a broader infrastructure investment environment for private investors since the participation of the private sector will pave the way for project preparation and financing. Moreover, the bond is a good opportunity for the Istanbul Municipality as an issuer to cooperate with private insurance companies to improve the development of infrastructures in Istanbul.

In section 6.3.1, we analysed potential entities who, by investing in the resilience bond, can be involved in the resilient infrastructure project for Istanbul. Furthermore, as a system for investment in environmental, social and governance, ESG investing is one of the focused policies of governments such as Turkey. If a resilience bond were to be applied in the resilient development of Istanbul to procure the potential investments from the ESG investing market, it would simultaneously release the financial burden from the Turkish government and improve the resilience of Turkey's cities.

The present thesis aims to prove validity of the concept of Municipal resilience bond to support regional redevelopment and retrofitting projects in Istanbul. However, data is needed and awaited from the project in order to test the structure and mechanism of the proposed Municipal resilience bond. The data will serve many purposes, but most importantly it will help with the development of the bond pricing model, since fair guidance of price will smooth the transition for the bond to be published in the market. The present thesis proposes that, by coupling the data with the conceptual model of the Municipal resilience bond, the Turkish government will be able to raise capital for pre-catastrophe resilient infrastructure development and post-catastrophe financial repayment.

Chapter 7 The Impact of Pandemic Resilience Bond: A Consideration of Infrastructure Interdependency

7.1 Introduction

The outbreak of Covid-19 has exposed the shortcomings of health infrastructures and overloaded healthcare systems. Covid-19 has shown the world that most cities are unprepared for pandemic catastrophes, and the outbreak has brought global attention to both physical resilience and economic resilience in cities due to the inestimable losses wrought by the pandemic (Sharifi 2021). Along with the recognition and uncertainty associated with unpredictable and unstoppable catastrophes, resilience is an increasingly essential component in hedging the growing exogenous and endogenous pressures of interconnected urban systems (Moglia et al. 2021). As per Linkov (2021), the enhancement of urban resilience was well recognised long before the outbreak of Covid-19, but the knowledge focuses mainly on earthquake risks rather than resilience to outbreaks of disease and pandemics. However, the current pandemic has not only exposed the vulnerabilities of urban systems, but has also shed light on the importance of planning for future resilient cities (Banai 2020). Therefore, enhancing urban resilience in the face of a global pandemic is topping the agendas of many local authorities;

The 2019 pandemic is an alert to the consequences of inadequate investment in public health infrastructures globally, and is also a reminder that the future of cities and the health of communities depends on sufficient investment in public health infrastructure (Gee 2020). However, Brugmann (2012) state that the rough estimation of the global urban infrastructure expenditure from 2005-2025 will be $200 trillion, where the planning investment in the urban infrastructure assets is 300 times more than the available adaptation funds. The economic situation worsened after the outbreak of Covid-19. There is consensus by Szmigiera (2021) that Covid-19 has inflicted severe negative impacts on global economics. The recent estimation from Statista in 2021 shows that economic losses in the best case from Covid-19 is 5.6% of global GDP. Pandemic risks have received less attention than economically destructive natural disasters such as wildfires, hurricanes and earthquakes; therefore, coverage of pandemics from individual insurance is limited (Hartwig et al. 2020). The situation only changed in 2017 when the World Bank launched the first pandemic catastrophe bond to transfer pandemic risks in developing countries to the financial market. Labbe (2017) confirms that the pandemic catastrophe bond issued by the World Bank is indeed the first-ever instrument dealing with global infectious diseases and transfers the risks to the financial market. Although enhancing urban economic resilience can hedge cities from future unforeseen catastrophe risks physically and economically, the bond has several issues. As long-term needed and beneficial developments, urban resilient infrastructure projects contain higher opportunity costs to compete with other more immediate projects. Financing for resilient projects and justifying their upfront funding are often the most common challenges for public and private sectors. Bhattacharya et al. (2012) state that financing infrastructure investments is requiring large risks capital for the upfront investment involved in the initial development and construction phase, because the revenue streams associated with policy uncertainty and affordability are the main risks faced by many projects; this is one of the most common reasons for many un-bankable projects. In response, this chapter introduces a pandemic resilience bond which can enhance physical and economic resilience for cities, be utilised when faced with unexpected health crises, and can overcome the drawbacks of the World Bank's Pandemic Catastrophe bond.

7.2 Background

7.2.1 Urban (economic) resilience to global pandemics

The Covid-19 pandemic has significantly stressed public health systems around the world. For example, research from Dattilo et al. (2020) assessed the potential overload of intensive care units across 50 of Mexico's central cities and found that public health infrastructures are in short supply in terms of hedging future potential pandemics. Furthermore, Covid-19 has revealed many issues and vulnerabilities in cities where citizens live in close proximity; a robust public health infrastructure is therefore essential. Afrin et al. (2021) show that public health infrastructures, proper sanitation and social distancing approaches should be highlighted because the enhancement of public health infrastructures has been identified as the practical 'hardware' to respond to pandemics.

Urban resilience is a significant research topic where researchers and policymakers address risk issues that could arise in cities if unexpected catastrophes from natural and man-made events were to occur (Sharifi 2020). Urban resilience has been defined as “the ability of an urban system and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales – to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity” (Meerow et al. 2016; Pamukcu-Albers et al. 2021). Whereas the UNCDF (2020) defines urban economic resilience as, “the capacity and related capabilities of urban communities to plan for, anticipate negative shocks, including long-term stresses, to their economies, reallocate and mobilize resources to withstand those shocks, recover from the shocks, and rebuild at least to pre-crisis levels, while placing their economies on the path to sustainable economic development and simultaneously strengthening their capacity to deal with any future shocks.” However, the global spread of Covid-19 has unsettled the existing urban resilience priorities in natural catastrophes. Sharifi and Khavarian-Garmsir (2020) argue that research on urban resilience now has an unprecedented opportunity to take action toward understanding the effects (and mitigate the impacts) from pandemics. According to Moglia et al. (2021), promoting urban resilience in the wake of a pandemic should be appropriately evaluated, and based on transforming how planning and governing cities are carried out, there are three urban missions: accelerating urban mobility transition, attaining regenerative urban development and creating resilient urban infrastructure. The development of urban resilience should be tailored to fulfil specific local policy requirements related to geographic, socio-economic and environmental aspects (Cities (2018).

The outbreak of Covid-19 brought global attention to both physical resilience and economic resilience because of the inestimable losses. According to the World-Bank (2020), global GDP is expected to be 3.2% below the pre-Covid-19 situation, which has led to a tightened global financial condition. However, the lack of political will and persistent underinvestment in the public health system continuously prevents public health systems from developing at all levels, even in wealthy countries like the United States (Maani and Galea 2020). The economic impact of the Covid-19 virus around the world cannot be understated. As the most significant and sensitive indicator, the global stock markets were greatly influenced. Fernandes (2020) discusses that the UK and German stock markets dropped 37% and 33%, respectively, in their performance; Brazil has ranked as the most impacted stock market in the world, decreasing by 48%. The oil, gas and coal industries have been the hardest hit. According to Ayittey et al.

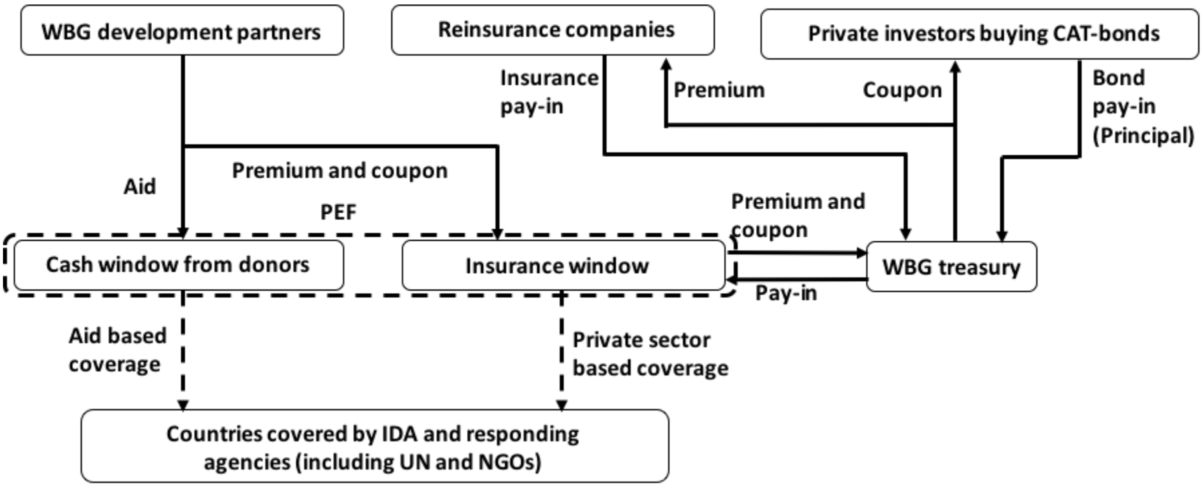
(2020), the coronavirus pandemic instigated a major recession in tourism markets, especially in China, which previously had 6.3 million Chinese tourists during the Chinese New Year holidays in early 2019. Such huge losses may lead to a limitation of ready-to-reimbursement funds because the principal may only be raised from donations and investments.

7.3 Mechanism and challenges of the World Bank pandemic catastrophe bond

Ever since the Ebola virus outbreak in 2014, health authorities around the world have sought to address their health systems and social wellbeing issues. The World-Bank (2017) launched a first-ever pandemic catastrophe bond, which was specially designed to hedge the unpredictable losses from epidemic events. The pandemic catastrophe bond was issued via the International Bank for Reconstruction and Development (IBRD) in June of 2017. As one of the five member institutions of the World Bank Group, the IBRD aims to support the Pandemic Emergency Financing Facility (PEF), which funds developing countries to overcome pandemic events. The Catastrophe bond has been applied by the World Bank as the financial solution.

Figure 7-1 depicts the mechanism of the World Bank Pandemic Catastrophe Bond; it is designed as a regular bond that private investors purchase from the World Bank Group (WBG) treasury and receive coupon payments regularly. Then, the WBG treasury works as the intermediary seeking insurance services from reinsurance; it pays a premium to reinsurance companies and coupon payments to private investors. In the meantime, the WBG treasury will also receive donation funds from development partner countries that are used to support the payment of the premium and coupon.

Figure 7-1 World Bank Catastrophe bond mechanism



Source: (Stein and Sridhar 2017)

The principal will be returned to private investors when the pandemic Catastrophe bond matures; otherwise, the money goes to countries covered by the International Development Association (IDA) and responding agencies, including the United Nations (UN) and Non-Governmental Organisations (NGOs) suffering from pandemic events. The Pandemic Emergency Financing Facility (PEF) is comprised of two windows: the ‘cash window,’ where Germany donates 50 million Euros to cover the diseases that have not been covered by the ‘insurance window’ since 2018; the ‘insurance window’ is divided into two tranches, where class A covers flu and coronavirus, and class B covers Filovirus, Coronavirus, Lassa Fever, Rift Valley Fever, and Crimean Congo Hemorrhagic Fever. The bond amounts are $225 million with coupon payment of 6 months LIBOR +6.5% in class A, and $95 million with coupon payment of 6 months LIBOR + 11.1% in class B (IBRD 2017). According to Stein and Sridhar (2017), the World Bank pandemic bond not only provides an opportunity to raise private money to hedge pandemic risks, but also creates a new market for pandemic risks. Many developing countries and governments appreciate the bond because of the free financial risk coverage due to pandemic events.

Although the World Bank paid $132.5 million to some of the poorest countries affected by the coronavirus in April 2020 (Gross 2020), the late payment conditions have led to heated discussions. According to the IBRD (2017), the payment condition is only triggered under specific and significant conditions: 1) When total confirmed deaths relating to the eligible event are greater than, or equal to, 2500 for Class A, and 250 for Class B; 2) The period of the eligible event is more than, or equal to, 12 weeks (84 days) for both classes; 3) The ratio of confirmed cases to total cases meets the threshold after 12 weeks for both classes; 4) The pandemic occurs in more than one country (which must be at least one IBRD or IDA country). Taking the view of The Guardian UK newspaper, Erikson and Johnson (2020) lament that the bond does not support countries; instead, the late trigger of the World Bank pandemic bond is "waiting for people to die." The reimbursement may not be delivered immediately because the payment condition is triggered only if the death number and growth ratio meet the requirements 12 weeks after the initial outbreak. However, as Anderson et al. (2020) state, the WHO has given evidence showing that the incubation of coronavirus is 5 to 6 days. Furthermore, Wölfel et al. (2020), among others, also demonstrate that the first 7 days are the most important to the recovery because the pharyngeal virus shedding is very high during the first week. Therefore, repayment may not efficiently help to prevent the spread of coronavirus due to the late trigger process. In other words, repayment from the World Bank Pandemic Catastrophe bond misses the best recovery time from the initial outbreak. A second problem with the pandemic bond is its restricted coverage; it cannot effectively help to prevent widespread coverage of the coronavirus beforehand. According to the prospectus from the IBRD (2017), the World Bank pandemic bond only covers the poorest countries (IBRD or IDA members). Nevertheless, the pandemic event has not only led to a shortage of frontline workers but has also increased the pressures on health infrastructure systems most everywhere. Unfortunately, none of the hardest hit countries, e.g., China, Italy, United States, and Iran, had World Bank pandemic bond coverage. A third problem is that private investors may be less attracted because the worst pandemic of our time has wiped out a huge value to assets in the global market that nearly no entity can benefit from. According to Alloway (2020) from Bloomberg, the recent reimbursement fund is supported mainly by donor countries; Japan has donated $50 million and Germany gave $15 million. Also, the International Development Association (IDA) offered a loan of $50 million to fill the vacancies of funds because IDA and governments were able to obtain cheaper sources.

International Aid from the World Bank and donor countries to the poorest countries may be a faster solution than the delayed trigger process from the bond. For example, the European Commission has proposed a €1 trillion recovery fund to support recovery from Covid-19. This fund could be an efficient instrument toward the recovery of economies; it aims to reduce firm closures in hit-hard countries (Motta and Peitz 2020). The lack of attractive investment in the market is unlikely to lead to wider expansion of the Catastrophe bond because repayment relies on replenished funding from donor countries and institutional loans. In this way, the World Bank pandemic catastrophe bond shows fewer advantages in attracting investors from the public and private sectors. To address the gap, this chapter proposes a pandemic resilience bond that can fulfill the needs of global communities by bringing opportunities to support the development of urban economic resilience in the event of future unpredictable pandemic catastrophes.

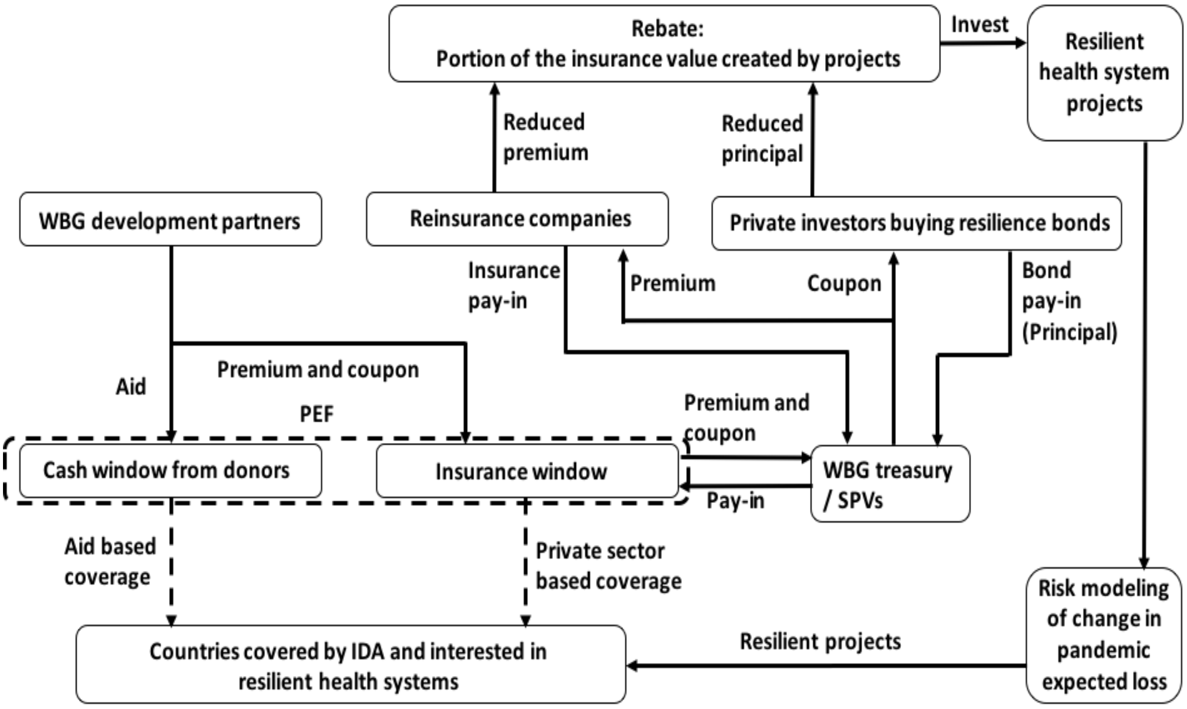
7.4 A conceptual model of pandemic resilience bond

The World Bank pandemic catastrophe bond has worked as an example offering a new opportunity to protect health systems by applying private funds. It offers reimbursement funds in post-pandemic economic losses for the poorest countries. However, as discussed above, the aftermath repayment system is unlikely to improve urban resilience against global pandemics, and instead "waits for the pandemic to occur." The improvement of urban resilience should include preparedness of urban infrastructure system projects in advance, e.g., hospital upgrades, health surveillance systems, vaccine laboratories, and health worker training centres should be the focus rather than having to depend only on insurance. The resilience bond fulfils the requirement of the above situation due to its flexible use of the rebate. However, as a newly published bond, the resilience bond has not been applied to pandemic-related research, thus revealing a hole in urban (economic) resilience development.

Based on previous experience, institutional investors are limited by several challenges, including lack of incentive regulations, absence of suitable financing vehicles, lack of expertise in investment and risk management, no appropriate investment data or benchmarks for infrastructures, and problems of transparency and viability (Della Croce and Yermo 2013). As the demand for resilient health infrastructure projects continues to increase, promoters are all expecting that cheaper possible debt can be gained via a variety of financial tools. Thus, bringing financing urban (economic) resilience issues to the bond market to attract more private investors is probably the most dynamic area for institutional investors who expect innovations. Moving the traditional (solely) public investment in the health system into the public-private partnership to attract more private investors is highly anticipated. The resilience bond contains advantages to attract a range of investors because it reduces the risk to the whole system by investing in resilient projects thereby decreasing the probability of losing money. Therefore, this study proposes a pandemic resilience bond to help develop a resilient health system and protect the system with insurance services. The bond shows more advantages to preparing the human health services in advance, which enhances the urban (economic) resilience to unpredictable future pandemic events.

Figure 7-2 depicts the mechanism of the pandemic resilience bond, which has been adapted by combining the pandemic catastrophe bond issued by the World Bank Group (WBG) with the unique function of the resilience bond. In the proposed pandemic resilience bond mechanism, the "Cash window" and "Insurance window" are similar as the Word Bank catastrophe bond, because the bond can still receive funds from donor countries. However, the pandemic resilience bond offers a unique 'rebate' function on top of the pandemic catastrophe bond, which can be applied to support the enhancement of the current health system with any eligible resilient infrastructure projects, e.g., upgrading a hospital. This design is likely to attract many public and private investors who are interested in the benefits of building resilient infrastructures. Investors purchase the resilience bond through the WBG treasury or any SPV, which works as an intermediary agent between the reinsurance companies and investors. In addition, the unique function of the pandemic resilience bond offers an upfront fund for resilient health system projects in advance, which will help the countries covered by the bond to prepare the health system for an unpredictable pandemic in the future. A third-party evaluator assesses the project and builds a risk model to forecast the risks mitigated from the resilient infrastructure project to the current health system. In the meantime, the reduced risks are quantified in a rebate form and reinvested to support the development of the resilient infrastructure project.

Figure 7-2 Pandemic resilience bond mechanism



Sources: adapted from (Stein and Sridhar 2017) and (Re:Focus 2015)

The main customers of resilience bonds are investors from capital and insurance markets who are switching from catastrophe bonds and are interested in benefiting from investment in infrastructure projects. A pandemic resilience bond also brings opportunities for the more capable insurance and capital markets to invest in resilient health system projects. In doing so, the original coverage from the pandemic catastrophe bond can be expanded to cover more countries interested in preparedness in their health systems and help with the enhancement of urban (economic) resilience globally.

7.5 Infrastructure impact simulation

As one of the most important factors for maintaining functionality and stability in societies, infrastructure systems continuously encounter challenges from natural and man-made catastrophes (Pant et al. 2014). For instance, as one of the five critical infrastructures, health infrastructures have been at the forefront since the beginning of the Covid-19 pandemic. Given that, according to Pant et al. (2014), different infrastructure sectors are interdependent within larger systems, as infrastructure networks become increasingly interconnected, any failure of one infrastructure could instigate cascading failure across multiple infrastructure sectors, bringing significant losses to whole economies (Kelly 2015). The demands and pressures posed on health care sectors during the pandemic demonstrates to the world that the cascading effects between the health care infrastructure sector and other sectors are real and significantly high. Hence, a catastrophic event impacts all related sectors directly or indirectly if any single critical infrastructure fails to operate. Preliminary work on the impacts of global pandemics was undertaken by (Orsi and Santos 2009; Santos et al. 2009; Santos et al. 2013); they conclude that a large-scale outbreak of pandemics may lead to cascading effects to the workforce sectors and cause numerous losses, illnesses and death.

In this section, we simulate the cascading impacts of the shortage of health infrastructures during the global pandemic to match the increasing demand, which has a knock-on effect on other industry sectors based on the input-output equilibrium theory. To measure the influence of the interdependency between different infrastructure sectors in various industries, the classic input-output (I-O) model of Leontief (1937) is applied. Leontief's model is well known for quantifying the interdependencies between different regional economies and different industry sectors in a nation. The present study runs the simulation under the assumption that the pandemic event leads to a 50% increase in demand for human health services; we thereafter measure the economic impacts on related industry sectors. Using the United Kingdom's latest 2016 input-output data enables us to complete the measurement. Thereafter, a pandemic resilience bond is proposed, which shows the advantage of developing the human health services sector in advance, instead of government response or post-repayment from insurance.

According to Miller and Blair (2009), Leontief's I-O model represents an equilibrium in a nation, region or state, that the supply and demand are equal and satisfy the requirements from each industry sector. The total output for each sector can be represented by the equation:

$$\begin{aligned} x_1 &= z_{11} + \dots + z_{1j} + \dots + z_{1n} + f_1 \\ &\vdots \\ x_i &= z_{i1} + \dots + z_{ij} + \dots + z_{in} + f_i \\ &\vdots \\ x_n &= z_{n1} + \dots + z_{nj} + \dots + z_{nn} + f_n \end{aligned} \tag{7.1}$$

where

x indicates total output for each industry sector;

z represents matrix of domestic use in basic prices;

f shows final exogenous demand for each sector.

In the I-O model, the input from sector i will be purchased by sector j; therefore, the coefficient between sector i and j can be represented by the ratio "A", which is called technical coefficient:

$$A = a_{ij} = \frac{z_{ij}}{x_j}\,, \qquad (7.2)$$

where
z_{ij} is the value of sector i purchased by sector j;
x_j is the total output of sector j.

By surmising Eqs. (1) and (2), the equilibrium from Leontief's I-O model can be encoded in the following equation:

$$x = Ax + f, \qquad (7.3)$$

where
x is amount of production output from all industries;
A stands for the $n{\times}n$ technical coefficients matrix of production;
f indicates the final demand.

The input-output model is used to evaluate the total economic impact associated with a change in industry output or a change in the demand for one or more commodities. As per the model, the production output from each industry should meet the demand from other related industry sectors. This study assumes a catastrophic event, such as Covid, has negatively impacted productivity in the health care service infrastructures, leading to cascading impacts in many related industries during the outbreak. In the analysis of the interdependency of infrastructures in different industry sectors, (Haimes et al. 2005b; Haimes et al. 2005a) find that an inoperability of a system may be triggered by one or multiple hits from catastrophes and influence several interconnected industry sectors. To measure the impacts to related industry sectors from a change of demand in the human health services sector, a $n{\times}n$ matrix $I = \begin{matrix} 1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 1 \end{matrix}$ will be set to calculate the new outputs from other sectors:

$$(I - A) * x = f \tag{7.4}$$

The output can be indicated as $x = (I - A)^{-1}f$, where $(I - A)^{-1}$ is called the Leontief inverse noted by "L". Then we will obtain:

$$x = L * f \tag{7.5}$$

As Miller and Blair (2009) show, all industry sectors in the input-output table fulfil the Leontief I-O model where the make of product is equal to the use of materials by each sector. Therefore, a change in demand in any sector will influence some related industry sectors and lead to a new output to keep the equivalent of the input and output:

$$x_{new} = L * \ f_{new}, \tag{7.6}$$

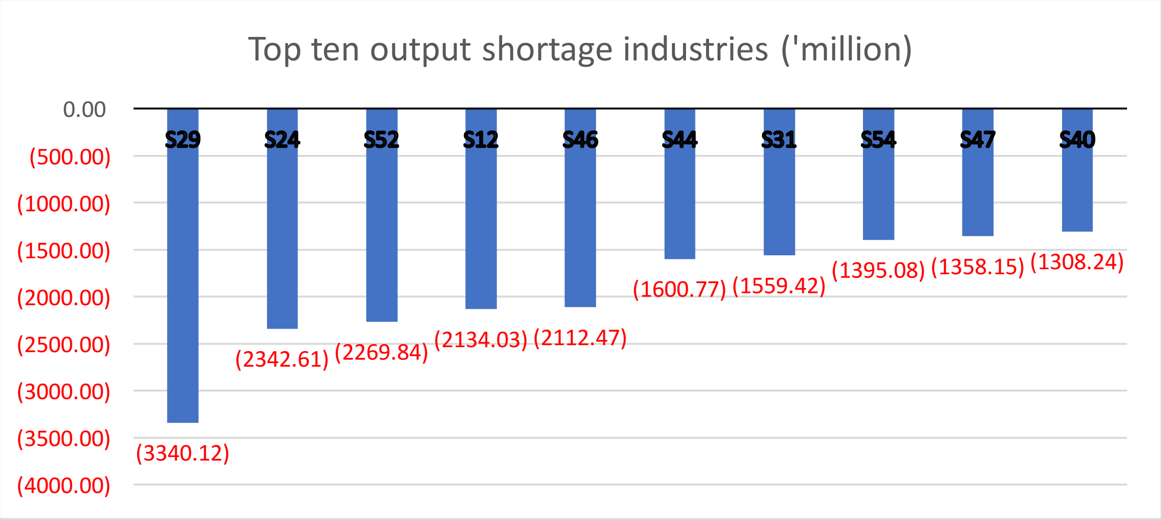
where
x_{new} is new output;
f_{new} is new demand due to catastrophic events.

In the analysis, the simulation is conducted by applying the UK industries with the known information from the input-output table. As the input-output table in the Office for National Statistics (ONS), the UK industries are divided into 64 sectors and human health services are recorded as sector 57 (S57) in the I-O table. Then, a simulation is conducted by assuming that the pandemic event occurs and leads to an increase in demand for human health services. However, the shortage of health infrastructures in the UK is hard-pressed to meet the increasing demand, which leads to a shortage in the human health services sector. As the characteristic of Input-output table, the supply and demand are equally stated in the I-O table so as to keep the equilibrium of supply and demand. All other industries have to raise their outputs to fulfil the rise of demand in human health services.

However, under the situation of global pandemic, the increasing demand for health infrastructure has caused a decrease of output from other industry sectors. To quantify the economic impacts, we assume the pandemic event leads to an increase in demand for the human health services sector by 50%. Based on the input-output equilibrium, a 50% increase in demand in the sector will require the support of an increase of 73% in productivity from other industry sectors. However, illness and lockdown policies have degraded all industries due to the lack of a workforce. The shortage of outputs hardly meets the requirement of the increased demand for human health services. On the contrary, the shortages in the health care system lead to a slow treatment process for the workforce, thus creating a vicious circle in the recovery from pandemic events.

The increasing demand from sector 57 has led to a decrease of output in almost all industry sectors. Figure 7-3 lists the top 10 output shortages in industry sectors. The details for the different sectors indicate in black type that, S29 is Wholesale trade services, except for motor vehicles and motorcycles; S24 is Electricity, gas, steam and air-conditioning; S52 is Employment services; S12 is Basic pharmaceutical products and pharmaceutical preparations; S46 is Legal and accounting services; services of head offices; management consulting services; S44 is Real estate services, excluding imputed rents; S31 is Land transport services and transport services via pipeline; S54 is Security and investigation services, services to buildings and landscapes; office administration, office support and other business support services; S47 is Architectural and engineering services, technical testing and analysis services; S40 is Computer programming, consultancy and related information services.

Figure 7-3 Top 10 output shortage industries



From the result, we can observe that the wholesale trade services sector (S29) is most affected; it has to increase by 3,340.12 million output during a global pandemic in order to match the increase of the 50% demand. However, with the lockdown and illness of workers, the wholesale trade services sector faces a shortage of 3,340.12 million output to support the equilibrium. The pandemic event has degraded the workforce across industries, but especially in the wholesale trade services sector because high-density populated areas put more people in danger of infection. Coronavirus is similar to many other dangerous viruses in that it is highly transmissible and, according to Santos et al. (2009) these highly transmissible viruses cause untold numbers of deaths in the elderly, and individuals with immunocompromised and underlying health conditions.

Therefore, to improve the health care infrastructure sector may improve overall resilience to all infrastructure sectors, and also strengthen urban (economic) resilience through the cooperation between different infrastructure sectors. Moteff (2012) discusses how the resilience of a critical infrastructure asset could be enhanced by giving it priority access to scarce critical resources, thereby maintaining its services or getting its services back online more quickly to aid in general community recovery. Since avoiding shocks is impossible, to focus on improving the urban economic resilience of interdependent infrastructures via pandemic resilience bonds denotes the ability to bounce back and operate under new stable regimes.

7.6 Conclusion

The outbreak of the global pandemic in 2019 has uncovered the shortcomings of health care infrastructure, leading to a shortage of productivity in critical industries, increasing pressures on the workforce, and exposing a fragile human health services sector. Understanding the weaknesses of the health care infrastructure sector and giving early preparation to strengthen the sector and introduce resilient projects is likely to make the overall system more resilient, of which the core component is to build urban (economic) resilience. Resilience has become a popular word in recent years and is found frequently in natural catastrophic events reports or critical infrastructure protection policy papers. However, the Covid-19 pandemic has demonstrated to the world that the knowledge of urban (economic) resilience should not only stay at the level of natural catastrophes, but should also include the preparedness of human health services in advance and save more lives and money for future unknown diseases. However, there are several barriers to financing urban economic resilience for global pandemics, especially after the outbreak of Covid-19, such as the limited financial capability for cities, fewer studies on the effects of the pandemic, and lack of health care infrastructure collateral. Alternative financing tools, such as resilience bonds are designed and aimed to overcome the instability of cities' financial systems that operate largely on self-interested speculation by directing investment into a productive 'bowl' of enhancing resilient infrastructure projects. The sufficient development of a pandemic resilience bond will effectively resolve fiscal issues for governments and cities while also improving infrastructure system resilience by transforming an economy through actions grounded in resilient projects. Therefore, we propose the conceptual model of a pandemic resilience bond, which has more ability to cover the weaknesses of the World Bank pandemic catastrophe bond.

A resilience bond is a newly published bond that breaks the fund constraints of resilient infrastructure investment for nations. It expands the potential investor range by combining the infrastructure investment market with the insurance risk market. Furthermore, it creates a potential market for infrastructure investment between different infrastructure sectors. The pandemic resilience bond is similar to the World Bank's pandemic catastrophe bond, but its mechanism is enhanced in the provision of dual functions that offer insurance services and investment in resilient health care infrastructure projects and ensure that the health infrastructure system continues working during a pandemic. As an alternative tool, it can likely shift the fulcrum of funding pressures away from governments to the more potential capital market and provide insurance protection simultaneously. The current financial trend is motivated by the desire to offer far more than a financial return on investment and aims to motivate people to "move their money out of mainstream financial institutions and into their platforms precisely in order to deliver wider social and environmental benefits." The pandemic resilience bond creates more opportunities for the resilient development of nations and cities to improve their ability to prepare and protect their health infrastructures in advance to be more resistant to future unknown pandemics.

Chapter 8 : Conclusions

8.1 Key findings

In this century, the world is confronted with new challenges from the increasing rate of catastrophic events. More frequent and severe floods, hurricanes, earthquakes, rising sea levels, and melting glaciers directly affect the human infrastructure systems essential to the daily function of the world's societies. Exposure to more catastrophes means that when interdependent infrastructures such as transportation, flood defense, and supply chains do experience a catastrophic event, the result can be a cascading failure of colossal proportions. Normal daily life is upended. Therefore, one can conclude that early preparation of resilient infrastructure is gaining more and more attention from public authorities globally because such systems are better able to mitigate damages caused by natural and human catastrophes.

Building resilient infrastructure is one of the significant sustainable development goals of the United Nations, which aims to achieve a better and more livable future for the world. However, considering the current level of infrastructure investment, a persistent funding shortfall is widening the gap between resilient infrastructure projects and investment. As the most problematic global issue, financing infrastructure projects imposes a heavy financial burden on world governments due to insufficient public resources with a high opportunity cost. Private investors have thus been identified as an optimal solution to support the development of infrastructures able to persist despite catastrophes. Attracting more private investment in resilient infrastructures has fostered the application of financial tools such as fixed-income securities and insurance-linked securities. The literature review in chapter 2 showed that the involvement of financial market bond investors may efficiently move the finance fulcrum away from traditional (sole) public investment to public-private partnerships (PPPs), where more opportunities for innovation can take place.

As discussed in section 2.1, fixed-income securities financial tools have been applied widely in the development of infrastructure. Green bonds and project bonds can effectively attract private finance to join in the investment of infrastructure and close the public-sector funding gap. However, through the review of the literature, we concluded that the application of fixed-income securities may only be capable of raising investment funds for the construction of infrastructures, not for post-catastrophe rebuilding and maintenance. Therefore, most entities are likely to need extra protection services from insurance to hedge the unexpected financial losses due to catastrophes. The literature review also discussed how many countries still encounter the problem of fewer insurance products created especially for infrastructure. Lacking insurance protection may delay much-needed maintenance after a catastrophe and worsen into cascading failures across the entire infrastructure system.

Along with the development of the current modern infrastructure network, the spread of applying insurance services in the infrastructures has brought insurance-linked securities to the forefront in the financial market; such a ready-for-use financial repayment may reduce the default risks for insurance companies. Furthermore, immediate repayment will ensure the recovery of the infrastructure system to its equivalent original level to continue operations. This concern was addressed in the literature review of the present thesis.

In section 2.2 we reviewed the most popular insurance-linked security, the catastrophe bond, which brings advantages by raising the financial reimbursement funds and is ready to be used for the repayment of future catastrophes. However, from the review, we found that the application of catastrophe bonds may only contain the function to repay the financial losses aftermath of the catastrophe, rather than prepare the infrastructure system to be resilient in advance in order to reduce the risk of losses. Many societies have begun to realise that improving the resilience of infrastructures may reduce the probability of failure of the whole system and bring further advantages, as the infrastructures persist, even when unexpected catastrophes occur. We therefore paid close attention to the newly designed insurance-linked security known as the *resilience bond*.

As the review in section 2.3 has demonstrated, the resilience bond not only offers a similar insurance reimbursement function like the traditional catastrophe bond, but it also provides an upfront investment fund to support the development of resilient infrastructure projects. The resilience bond could be one of the best possible financial tools to support the development of resilient infrastructure for individuals, corporations and governments around the world. The unique ‘rebate’ function of resilience bonds offers an upfront investment fund that avoids the financial stress associated with limited public resources. However, because it is such a new insurance-linked securities product, there is little literature dedicated to its performance; nor is it completely understood how to price the bond for capital market investors. Therefore, one of the overarching objectives of this research is to help governments and public authorities release their financial burden and foster greater investment in resilient infrastructure projects. If a government chooses to apply a resilience bond to build resilience within an infrastructure system, that government will generate upfront investment funding for projects, improve the resilience for the city, and hedge unexpected losses in advance. Moreover, the present study has also discovered the impact of the resilience bond in resilient infrastructure system development via testing two case studies in China and Wales. We first conducted a critical review and analysis of the traditional insurance-linked securities pricing model so as to build the resilience bond pricing model. Then we carried out two case studies to examine the resilience bond under different catastrophe scenarios: supply chain disruptions in China and flooding in Towyn Wales, where we investigated the mechanism of resilience bond with the investment in resilient infrastructure projects. We also conducted a comparative review of the feasible financial tools in section 2.4. By comparing the bonds in the context of supporting the development of resilient infrastructure, we concluded that fixed-income securities are designed to be involved in large-scale infrastructure projects. For example, the Green bond is used extensively in China and America for 'green' environmentally-related infrastructure projects. However, under the circumstances of investing in resilient infrastructure projects, the resilience bond shows more advantages thanks to its unique and innovative function.

In chapter 3 we critically reviewed the methodology for general bond valuation and the traditional insurance-linked securities pricing model. The study goal was to build a proper pricing model for the newly published resilience bond, since it is designed based on the traditional catastrophe bond. From the revision, we concluded that the resilience bond contains a unique function, the 'rebate,' to re-invest in the resilient infrastructure project. In this way the pricing model should focus on the simulation of the dynamic interest rate, dynamic consequences (claims), and the impact of the resilient infrastructure on the whole system. We have also designed an impact factor to quantify the effects of the project on the whole infrastructure system and the percentages (resilience) of the risks reduced. The price of resilience bonds varies according to different catastrophes and resilient infrastructure projects. To calibrate the pricing model accurately for each condition, we carried out two case studies in chapters 4 and 5 which have applied resilience bonds in catastrophes with different resilient projects.

From the theoretical part of chapters 1 and 2 in the thesis we can report some key findings:

- The development of infrastructure should not only focus on the attractiveness of private finance but should also consider the resilience of the infrastructure system to persist in future catastrophes and risks. The improvement of resilience in the infrastructure system may mitigate the risk of failure of the infrastructure network and reduce potential financial losses. Moreover, a resilient infrastructure is likely to bounce back to an equivalent original level and decrease the recovery time, thus saving money and lives.

- The newly published resilience bond may bring more advantages than the traditional catastrophe bond, project bond, and green bond. The occurrence and consequences of unknown catastrophes have brought unexpected losses to countries. To reduce the unpredictable risks, the application of a resilience bond may not only provide post-catastrophe financial reimbursement to the entity suffering from the catastrophic events but may also offer an upfront investment fund to improve the resilience of the system, thereby reducing the risk of failure and financial losses.

- The existing literature on resilience bonds is limited in many aspects, e.g., design of the bond mechanism, potential issuers and investors analysis, the pricing model for the financial market, and scenario-based studies. Therefore, the present research has been dedicated to the analysis of previous research on insurance-linked securities and the resilience bond mechanism in three applications with different catastrophe scenarios.

From the two case studies of chapters 4 and 5 in the thesis, different catastrophe scenarios were simulated and considered to have processed the application of a resilience bond; the following conclusions can be drawn:

- In the first case study in chapter 4, we tested the resilience bond pricing model under the context of supply chain disruption in China using data provided from Willis Tower Watson (Shanghai). The research of an upgrade to the intermodal transportation port (ITP) project may improve the flexibility of the whole supply chain network efficiently to lower the failure of the whole goods movement network. By designing a measurement of the ITP project in section 4.4.2, the research simulated a supply chain network and analysed the resilience impact of the upgrade project to the hubs. We concluded that the impact of the project would generate a 6.07% resilience impact to the whole system, which means that the potential economic losses from unexpected supply chain disruption would be reduced by 6.07% by upgrading resilient infrastructure projects. In this way, a resilience bond could be one of the most effective financial tools for raising the upfront investment fund to upgrade the project, and in the meantime, provide insurance protection for post-catastrophe financial losses. Lastly, we provided guidance on the price, in accordance with the pricing model, that a 5-year supply chain resilience bond can be issued on 60.4 yuan over the 100 face value in the financial market.

- In the second case study in chapter 5, we tested the resilience bond pricing model by simulating flooding catastrophic events which will strike the flood defenses in Towyn, Wales under different surge levels. From the research, we concluded that an enhancement project to the flood defense system would reduce the probability of financial losses from a broken flood defense. A sensitivity analysis was also conducted to measure the influence of different resilience impact factors and parameters. In addition, we concluded that the application of a resilience bond may provide sufficient funding to support the enhancement project, which can thereupon release the financial burden of local public authorities. In the meantime, the insurance function of the resilience bond would help protect the communities living along the coast and lessen the risks from rising sea levels.

From the extension of concept in chapters 6 and 7, the thesis extended the the application of resilience bond in the global pandemic issues and multi-hazard disaster risk in Tomorrow's Cities project for Istanbul hub.

- In chapter 6, the study is dedicated in a UKRI GCRF project that aims to build a resilient Istanbul hub which capable to withstanding multiple hazards, especially earthquakes. From the research, we designed a conceptual model for a Municipal resilience bond for Istanbul and proposed the local municipality as the main issuer of the resilience bond. The research is awaiting data from research partners; cooperation is ongoing with Istanbul authorities.

- In chapter 7, we analysed the effects of using a resilience bond from its economic aspect. The study assumed that the resilience bond could be a useful financial tool to support the development of urban economic resilience under the current Covid-19 catastrophe. From the chapter, we found that the pandemic resulted in immeasurable economic losses to the world; preventative actions of the occurrence of such catastrophes are impossible. Prior to the present Covid-19 pandemic, the World Bank created a pandemic catastrophe bond designed to support the recovery of countries suffering from widespread health crises. However, the design of the pandemic catastrophe bond has been criticised for its 'late payment' and 'inadequate coverage'. The chapter therefore studied the application of resilience bonds which may efficiently support the development of urban resilience and provide insurance protection. As part of the urban fabric, health care infrastructures such as hospitals and clinics, are critical to the operation of an economy. Therefore, improvements to health care infrastructures may upgrade the whole system to be able to tolerate unexpected catastrophes. A resilience bond could be one of the optimal financial tools that offers investment funds and provides insurance protection.

The main strength of this research centres on our three case studies of resilience bonds, which help to spread the bond in the market, thus creating examples for entities interested in applying resilience bonds. Based on the pricing model, we have assessed the prices of resilience bonds under different catastrophes as guidance, which may help the bond be published in the capital market, since a clear and fair price for the bond could attract higher demand. The presence of the different types of resilience bond, e.g., supply chain resilience bond, flooding resilience bond, and earthquake resilience bond provides the opportunity for bond investors to understand the mechanism and effects of issuing resilience bonds in support of the development of future resilient infrastructure. The expansion of the market for resilience bonds could help save lives and reduce losses for individuals, corporations and countries by hedging future unforeseen catastrophes in advance.

8.2 Limitations

During the research, we encountered several limitations. Datasets are the most essential parts of research in data analysis and modeling, and it is here that we faced challenges from the lack of data. For example, in the first case study, we applied a resilience bond into the resilient infrastructure development for the supply chain in China. The case study used the dataset provided by Willis Tower Watson (Shanghai) to simulate the distribution of consequences for supply chain disruptions. However, the limitation to this case study is that the dataset only contains 3 years of supply chain disruptions because the insurance company may only save 3 years of data to evaluate the premium for customers. Besides, the real cost of an intermodal logistics port is hard to be obtained based on different location and different functions. Therefore, the percentage of the upfront fund from the rebate of resilience bond cannot be provided. In the Turkish case study, we are involved in a government project to design a resilience bond for the retrofit project in Istanbul. However, the research at present is only in its conceptual model stage of the Istanbul municipal resilience bond rather than in the process of pricing the model. We are awaiting data from Istanbul public authorities from a retrofit project to hedge earthquake catastrophes. The main data type needed in the research are the economic losses of the assets under the disaster, such as the when an earthquake occurs, the damage has caused economic losses to the city. Then, we can use the economic losses data to define the distribution, which will be used to forecast the economic losses in the future by combining the occurrence probability of the event. Another limitation of the research is the range of application of resilience bonds. The price of resilience bonds to be published in the market relates to different combinations of catastrophic events and resilient infrastructure projects. Therefore, the research only provides pricing guidance based on different scenarios rather than giving a general pricing model for resilience bonds.

8.3 Policy implications and future research

From the study, we found that preparedness in the form of resilience can mitigate the unpredictable financial losses from infrastructure failures. The Sustainable Development Goals, the blueprint of the United Nations, aims to build a better and more sustainable future for the world. To build resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation are among the 17 goals in sustainable development from the UN. In the 2030 agenda for sustainable development, global attention is mainly being given to infrastructure, especially public transport systems, goods delivery networks, and affordability, efficiency and convenience of transportation (United-Nations 2021). However, the gap between infrastructure investment funds and policies by governments and public authorities nevertheless continues to widen, thereby calling for the application of the resilience bond in future development of resilient cities, communities, and infrastructure networks. The Paris Agreement of 2016 has

also affirmed that developed countries should offer financial help to the less endowed, more vulnerable countries. Furthermore, climate finance is becoming a topic of some urgency due to the demand for large-scale investments in emissions mitigation and the need for financial resources to adapt infrastructures to be resilient to climate change (United-Nations 2017).
The resilience bond also has advantages when attracting entities who want to protect communities and natural habitats. For example, a Forest Resilience Bond (FRB) was applied in 2017 for forest restoration projects sponsored by Blue Forest Conservation which became to one of the most popular environmental related projects; this public-private partnership model is set up to deploy private finance in the investment of forest restoration projects on both private and public lands (Blue-forest-conservation 2017). As we have seen, the resilience bond's features widen the range of potential investors by attracting from both the public and the private sector. In the current insurance market, fewer insurance products have been involved in infrastructure assets because most people consider infrastructures as public goods; therefore, after catastrophes governments are deemed responsible for the rebuild and maintenance of infrastructures. However, we have shown in the previous chapters how governments are under significant financial pressure due to limited public resources and higher opportunity costs associated with different categories of investment.

Therefore, to reduce the burden on governments, the expectation of new insurance-linked financial tools in the market – with lower costs of capital to insurers and greater availability of affordable insurance to policyholders – would be welcome. Infrastructure is pervasive in the daily lives of billions of people, so providing affordable insurance to more people would have positive public policy implications. The proposal in this thesis, for the resilience bond to cover the weaknesses of the situation in the current market, aims to offer both investment funds and insurance protection for resilient infrastructure projects.

Several limitations have already been highlighted in the limitation section, but lack of datasets is the main concern for the present thesis, in particular is the absence of the resilience improvement data from Istanbul's building retrofit project, as well as data on the global economic losses of Covid-19. Future studies could, with data, test the conceptual framework and pricing model of the resilience bond in the context of Istanbul retrofit projects and in the context of global pandemic resilience. Future research could also inquire into whether an application of the resilience bond improves network resilience after a multiple node failure. Also, asking how different flood parameters, such as intensity, distance and geology impact the price of a flood resilience bond could yield useful results. Further tests with available data would help to enhance overall model performance and likely provide more accurate pricing of the resilience bond under different scenarios.

List of References

Aase, Knut (1999), 'An equilibrium model of catastrophe insurance futures and spreads', *The GENEVA Papers on Risk and Insurance-Theory,* 24 (1), 69-96.

Adger, W Neil (2000), 'Social and ecological resilience: are they related?', *Progress in human geography,* 24 (3), 347-64.

Afrin, S, Chowdhury, FJ, and Rahman, MM (2021), 'COVID-19 Pandemic: Rethinking Strategies for Resilient Urban Design, Perceptions, and Planning. Front. Sustain', *Cities,* 3, 668263.

Alloway, Tracy (2020), 'Do Pandemic Bonds work?', *Bloomberg* https://www.bloomberg.com/news/articles/2020-04-10/do-pandemic-bonds-work, (Accessed: 09/09/2022).

Almeida, Miguel (2020), 'Green Bonds Global State of The Market 2019', *Climate Bonds Initiative*.

Anderson, Roy M, et al. (2020), 'How will country-based mitigation measures influence the course of the COVID-19 epidemic?', *The Lancet,* 395 (10228), 931-34.

Arnold, Pierre, Peeters, Dominique, and Thomas, Isabelle (2004), 'Modelling a rail/road intermodal transportation system', *Transportation Research Part E: Logistics and Transportation Review,* 40 (3), 255-70.

Athavale, Manoj and Avila, Stephen M (2011), 'An analysis of the demand for earthquake insurance', *Risk Management and Insurance Review,* 14 (2), 233-46.

Ay, Deniz and Demires Ozkul, Basak (2021), 'The strange case of earthquake risk mitigation in Istanbul', *City*, 1-21.

Ayar, Burak and Yaman, Hande (2012), 'An intermodal multicommodity routing problem with scheduled services', *Computational optimization and applications,* 53 (1), 131-53.

Ayittey, Foster K, et al. (2020), 'Economic impacts of Wuhan 2019‐nCoV on China and the world', *Journal of Medical Virology,* 92 (5), 473-75.

Bachelet, Maria Jua, Becchetti, Leonardo, and Manfredonia, Stefano (2019), 'The green bonds premium puzzle: The role of issuer characteristics and third-party verification', *Sustainability,* 11 (4), 1098.

Baker, Malcolm, et al. (2018), 'Financing the response to climate change: The pricing and ownership of US green bonds', (National Bureau of Economic Research).

Banai, Reza (2020), 'Pandemic and the planning of resilient cities and regions', *Cities,* 106, 102929.

Barad, M and Sapir, D Even (2003), 'Flexibility in logistic systems—modeling and performance evaluation', *International Journal of Production Economics,* 85 (2), 155-70.

Barker, Lucy, et al. (2016), 'The winter 2015/2016 floods in the UK: a hydrological appraisal', *Weather,* 71 (12), 324-33.

Baryshnikov, Yu, Mayo, A, and Taylor, DR (2001), 'Pricing of CAT bonds', *preprint*.

Bates, Bryson, Kundzewicz, Zbigniew, and Wu, Shaohong (2008), *Climate change and water* (Intergovernmental Panel on Climate Change Secretariat).

Bates, Paul D, et al. (2005), 'Simplified two-dimensional numerical modelling of coastal flooding and example applications', *Coastal Engineering,* 52 (9), 793-810.

Batica, Jelena and Gourbesville, Philippe (2016), 'Resilience in flood risk management–a new communication tool', *Procedia Engineering,* 154, 811-17.

Bektas, Tolga and Crainic, Teodor (2007), *A brief overview of intermodal transportation* (CIRRELT).

Bennett, Oliver and Hartwell-Naguib, Sarah (2014), 'Flood defence spending in England', *House of Commons Library Standard Note SN/SC/5755*.

Berkeley, Alfred R. and Wallace, Mike (2010), 'A Framework for Establishing Critical Infrastructure Resilience Goals', *Final Report and Recommendations by the Council*.

Bhattacharya, Amar, Romani, Mattia, and Stern, Nicholas (2012), 'Infrastructure for development: meeting the challenge', *CCCEP, Grantham Research Institute on Climate Change and the Environment and G,* 24, 1-26.

Bigoni, Matteo (2019), 'Climate bonds standard Version 3.0', *Climate Bonds Initiative*.

Blackburn, Mike, Methven, John, and Roberts, Nigel (2008), 'Large‐scale context for the UK floods in summer 2007', *Weather,* 63 (9), 280-88.

Blue-forest-conservation (2017), 'Fighting fire with finance: A roadmap for collective action', *FOREST RESILIENCE BOND*.

Boffo, R and Patalano, R. (2020), 'ESG Investing: Practices, Progress and Challenges', *OECD*.

Bommer, Julian, et al. (2002), 'Development of an earthquake loss model for Turkish catastrophe insurance', *Journal of Seismology,* 6 (3), 431-46.

Bontekoning, Yvonne and Priemus, Hugo (2004), 'Breakthrough innovations in intermodal freight transport', *Transportation Planning and Technology,* 27 (5), 335-45.

Bontekoning, Yvonne M, Macharis, Cathy, and Trip, Jan J (2004), 'Is a new applied transportation research field emerging?—A review of intermodal rail–truck freight transport literature', *Transportation Research Part A: Policy and Practice,* 38 (1), 1-34.

Boudrias, Jean-Pierre, Kotin, Rebecca, and Suisse, Credit (2012), 'Project Bonds in Project Finance', *The Principles of Project Finance,* 1st Edition (9781315553931), 12.

Bouriaux, Sylvie and MacMinn, Richard (2009), 'Securitization of catastrophe risk: New developments in insurance-linked securities and derivatives', *Journal of Insurance Issues*, 1-34.

Braun, Alexander, Herrmann, Markus, and Hibbeln, Martin Thomas (2022), 'Common risk factors in the cross section of catastrophe bond returns', *Available at SSRN 3901695*.

Brealey, Richard A, et al. (2012), *Principles of corporate finance* (Tata McGraw-Hill Education).

Brealey, Richard A., Myers, Stewart C., and Allen, Franklin (2014), *Principles of corporate finance / Richard A. Brealey, Stewart C. Myers, Franklin Allen* (11th global ed. edn., The McGraw-Hill/Irwin series in finance, insurance, and real estate; Maidenhead: McGraw-Hill Education).

Brigo, Damiano and Mercurio, Fabio (2007), *Interest rate models-theory and practice: with smile, inflation and credit* (Springer Science & Business Media).

Brockway, Derek (2020), 'Flooding: Looking back on the 1990 Towyn devastation', *BBC News,* https://www.bbc.co.uk/news/uk-wales-51630850, (Accessed: 25/08/2022).

Brody, Samuel D, et al. (2017), 'Understanding the motivations of coastal residents to voluntarily purchase federal flood insurance', *Journal of Risk Research,* 20 (6), 760-75.

Bronstert, Axel (2003), 'Floods and climate change: interactions and impacts', *Risk Analysis: An International Journal,* 23 (3), 545-57.

Browne, Mark J and Hoyt, Robert E (2000), 'The demand for flood insurance: empirical evidence', *Journal of risk and uncertainty,* 20 (3), 291-306.

Brugmann, Jeb (2012), 'Financing the resilient city', *Environment and Urbanization,* 24 (1), 215-32.

Bruneau, Michel, et al. (2003), 'A framework to quantitatively assess and enhance the seismic resilience of communities', *Earthquake spectra,* 19 (4), 733-52.

Burnecki, Krzysztof, Janczura, Joanna, and Weron, Rafał (2011), 'Building loss models', *Statistical Tools for Finance and Insurance* (Springer), 293-328.

Butler, Catherine and Pidgeon, Nick (2011), 'From 'flood defence'to 'flood risk management': exploring governance, responsibility, and blame', *Environment and Planning C: Government and Policy,* 29 (3), 533-47.

Cabinet-Office (2011), 'Keeping the country running: natural hazards and infrastructure'.

Canabarro, Eduardo, et al. (2000), 'Analyzing insurance-linked securities', *The Journal of Risk Finance,* 1 (2), 49-75.

Capelle-Blancard, Gunther, et al. (2016), 'Environmental, Social and Governance (ESG) performance and sovereign bond spreads: an empirical analysis of OECD countries', *Available at SSRN 2874262*.

Caroline Miller, Smith , et al. (2014), 'Project bonds: Their growing role in global infrastructure finance', *WHITE & CASE*.

Carreras, Oriol and Kara, Amit (2017), 'Infrastructure in the UK - Time to rebuild?', *National Institute of Economic and Social Research*

Cestau, Dario, et al. (2019), 'Municipal bond markets', *Annual Review of Financial Economics,* 11, 65-84.

Chang, Stephanie E and Nojima, Nobuoto (2001), 'Measuring post-disaster transportation system performance: the 1995 Kobe earthquake in comparative perspective', *Transportation research part A: policy and practice,* 35 (6), 475-94.

Christensen, Claus Vorm and Schmidli, Hanspeter (2000), 'Pricing catastrophe insurance products based on actually reported claims', *Insurance: Mathematics and Economics,* 27 (2), 189-200.

Christofides, Stavros (2004), 'Pricing of catastrophe linked securities', *ASTIN Colloquium International Actuarial Association, Brussels, Belgium*.

Christopher, Martin (2016), *Logistics & supply chain management* (Pearson Higher Ed).

Christopher, Martin and Peck, Helen (2004), 'Building the resilient supply chain', *The international journal of logistics management,* 15 (2), 1-14.

Christopher, Martin and Lee, Hau (2004), 'Mitigating supply chain risk through improved confidence', *International journal of physical distribution & logistics management,* 34 (5), 388-96.

Cities, Building Resilient (2018), 'OECD Green Growth Studies The OECD Green Growth Strategy aims to provide concrete recommendations and measurement tools, including indicators, to support countries' efforts to achieve economic growth and development, while ensuring that natural assets continue to provide the resources and environmental services on which well-being relies. The strategy proposes a flexible policy framework that can be tailored to different country circumstances and stages of development. English Also available in: French'.

Cox, John C, Ingersoll Jr, Jonathan E, and Ross, Stephen A (1985), 'A theory of the term structure of interest rates', *Econometrica: Journal of the Econometric Society*, 385-407.

Cox, Samuel H and Pedersen, Hal W (2000), 'Catastrophe risk bonds', *North American Actuarial Journal,* 4 (4), 56-82.

Crainic, Teodor Gabriel (2003), 'Long-haul freight transportation', *Handbook of transportation science* (Springer), 451-516.

Crainic, Teodor Gabriel and Kim, Kap Hwan (2007), 'Intermodal transportation', *Handbooks in operations research and management science,* 14, 467-537.

Croson, David and Richter, Andreas (2003), 'Sovereign cat bonds and infrastructure project financing', *Risk Analysis,* 23 (3), 611-26.

Cummins, David, Lewis, Christopher, and Phillips, Richard (1999), 'Pricing excess-of-loss reinsurance contracts against cat as trophic loss', *The financing of catastrophe risk* (University of Chicago Press), 93-148.

Cummins, J David (2008), 'CAT Bonds and Other Risk‐Linked Securities: State of the Market and Recent Developments', *Risk Management and Insurance Review,* 11 (1), 23-47.

Cummins, J David and Trainar, Philippe (2009), 'Securitization, insurance, and reinsurance', *Journal of Risk and Insurance,* 76 (3), 463-92.

Cummins, J David and Weiss, Mary A (2009), 'Convergence of insurance and financial markets: Hybrid and securitized risk‐transfer solutions', *Journal of Risk and Insurance,* 76 (3), 493-545.

Dailami, Mansoor and Hauswald, Robert (2003), *The emerging project bond market: Covenant provisions and credit spreads* (3095: World Bank Publications).

Dattilo, Wesley, et al. (2020), 'COVID-19 most vulnerable Mexican cities lack the public health infrastructure to face the pandemic: a new temporally-explicit model', *MedRxiv*.

Dawson, R, Hall, J, and Davis, J (2004), 'Performance-based management of flood defence systems', *Proceedings of the Institution of Civil Engineers-Water Management* (157: Thomas Telford Ltd), 35-44.

Dawson, Richard J, Peppe, Roger, and Wang, Miao (2011), 'An agent-based model for risk-based flood incident management', *Natural hazards,* 59 (1), 167-89.

De Bruijn, Karin M (2004), 'Resilience and flood risk management', *Water Policy,* 6 (1), 53-66.

Della Croce, Raffaele and Yermo, Juan (2013), 'Institutional investors and infrastructure financing'.

Demuzere, Matthias, et al. (2014), 'Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure', *Journal of environmental management,* 146, 107-15.

Deutsche-Bank (2013), 'Project Bond Initiative - Project selection the key to success', *DB Research*.

DHL (2022), 'A look back at 2015: The top 10 supply chain disruptions', https://www.dhl.com/global-en/delivered/globalization/a-look-back-at-2015-the-top-10-supply-chain-disruptions.html, (Accessed: 12/08/2022).

Dobie, Michael (2011), 'Earthquakes and the design of infrastructure projects: experience from Indonesia', *ICE Asia Pacific Convention on Infrastructure Development in the Tropical Environment*.

Dollery, Brian, Byrnes, Joel, and Crase, Lin (2007), 'The infrastructure crisis in Australian local government: A proposed federal asset fund solution', *Australasian Journal of Regional Studies,* 13 (1), 3.

Dotoli, Mariagrazia, et al. (2013), 'A multi-agent decision support system for optimization of co-modal transportation route planning services', *52nd IEEE Conference on Decision and Control* (IEEE), 911-16.

Douglas, Ian (2009), 'Climate change, flooding and food security in south Asia', *Food Security,* 1 (2), 127-36.

Ebinger, Charles K and Zambetakis, Evie (2009), 'The geopolitics of Arctic melt', *International Affairs,* 85 (6), 1215-32.

Ehlers, Torsten, Packer, Frank, and Remolona, Eli (2014), 'Infrastructure and corporate bond markets in Asia', *conference volume of the 2014 RBA Annual Conference on "Financial Flows and Infrastructure Financing", July*.

Erdik, Mustafa and Durukal, Eser (2008), 'Earthquake risk and its mitigation in Istanbul', *Natural Hazards,* 44 (2), 181-97.

Erdik, Mustafa, et al. (2003), 'Earthquake risk assessment for Istanbul metropolitan area', *Earthquake Engineering and Engineering Vibration,* 2 (1), 1-23.

Erikson, Susan L and Johnson, Leigh (2020), 'Will financial innovation transform pandemic response?', *The Lancet Infectious Diseases*.

Erlinghagen, Sabine and Markard, Jochen (2012), 'Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change', *Energy Policy,* 51, 895-906.

Euroweek, London (2013), 'Project bonds advance as EIB enhancement lifts first Ofto bond'.

Familoni, KA (2006), 'The role of economic and social infrastructure in economic development: A global view', *Journal of Economic Perspectives,* 6 (4), 11-32.

Fernandes, Nuno (2020), 'Economic effects of coronavirus outbreak (COVID-19) on the world economy', *Available at SSRN 3557504*.

Fourie, Johan (2006), 'Economic infrastructure: a review of definitions, theory and empirics', *South African Journal of Economics,* 74 (3), 530-56.

Frascatore, Mark R and Mahmoodi, Farzad (2008), 'Long-term and penalty contracts in a two-stage supply chain with stochastic demand', *European Journal of Operational Research,* 184 (1), 147-56.

Froot, Kenneth A (2001), 'The market for catastrophe risk: a clinical examination', *Journal of Financial Economics,* 60 (2-3), 529-71.

García-Lamarca, Melissa and Ullström, Sara (2020), '"Everyone wants this market to grow": The affective post-politics of municipal green bonds', *Environment and Planning E: Nature and Space*, 2514848620973708.

Gee, Rebekah (2020), 'Aligning public health infrastructure and Medicaid to fight COVID-19', (American Public Health Association).

Gernay, Thomas, et al. (2016), 'Urban infrastructure resilience to fire disaster: An overview', *Procedia engineering,* 161, 1801-05.

Gichoya, David (2005), 'Factors affecting the successful implementation of ICT projects in government', *the Electronic Journal of e-government,* 3 (4), 175-84.

Glenn Richey Jr, R, Skipper, Joseph B, and Hanna, Joe B (2009), 'Minimizing supply chain disruption risk through enhanced flexibility', *International Journal of Physical Distribution & Logistics Management,* 39 (5), 404-27.

Global, FM (2007), 'Managing business risk through 2009 and beyond', *FM Insurance Company Limited, Windsor, Berks, UK*.

Glomm, Gerhard and Ravikumar, Balasubrahmanian (1994), 'Public investment in infrastructure in a simple growth model', *Journal of Economic Dynamics and Control,* 18 (6), 1173-87.

Goda, Katsuichiro (2013), 'Basis Risk of Earthquake Catastrophe Bond Trigger Using Scenario-Based versus Station Intensity–Based Approaches: A Case Study for Southwestern British Columbia', *Earthquake Spectra,* 29 (3), 757-75.

Golz, Sebastian, Schinke, Reinhard, and Naumann, Thomas (2015), 'Assessing the effects of flood resilience technologies on building scale', *Urban Water Journal,* 12 (1), 30-43.

Gomez, Laura and Carcamo, Ulises (2014), 'A multifactor pricing model for cat bonds in the secondary market', *Journal of Business Economics and Finance,* 3 (2), 247-58.

Görmez, Nihan, Köksalan, Murat, and Salman, F Sibel (2011), 'Locating disaster response facilities in Istanbul', *Journal of the Operational Research Society,* 62 (7), 1239-52.

Götze, Tobias and Gürtler, Marc (2018), 'Sponsor-and trigger-specific determinants of CAT bond premia: a summary', *Zeitschrift für die gesamte Versicherungswissenschaft,* 107 (5), 531-46.

Göymen, Korel (2000), 'Tourism and governance in Turkey', *Annals of Tourism Research,* 27 (4), 1025-48.

Gross, Anna (2020), 'World Bank pandemic bonds to pay $133m to poorest virus-hit nations', *Financial Times* https://www.ft.com/content/c8556c9f-72f7-48b4-91bf-c9e32ddab6ff, (Accessed:09/09/2022).

Guha-Sapir, Debarati, Hargitt, David, and Hoyois, Philippe (2004), *Thirty years of natural disasters 1974-2003: The numbers* (Presses univ. de Louvain).

Hachenberg, Britta and Schiereck, Dirk (2018), 'Are green bonds priced differently from conventional bonds?', *Journal of Asset Management,* 19 (6), 371-83.

Hagedorn, Dominik, et al. (2009), 'Choice of triggers', *The handbook of insurance-linked securities*, 37-48.

Haimes, Yacov Y, et al. (2005a), 'Inoperability input-output model for interdependent infrastructure sectors. II: Case studies', *Journal of Infrastructure Systems,* 11 (2), 80-92.

Haimes, Yacov Y, et al. (2005b), 'Inoperability input-output model for interdependent infrastructure sectors. I: Theory and methodology', *Journal of Infrastructure Systems,* 11 (2), 67-79.

Hall, Robert E and Jones, Charles I (1999), 'Why do some countries produce so much more output per worker than others?', *The quarterly journal of economics,* 114 (1), 83-116.

Hao, Yan, Armbruster, Dieter, and Hütt, Marc-Thorsten (2015), 'Node survival in networks under correlated attacks', *PloS one,* 10 (5), e0125467.

Hartwig, Robert, Niehaus, Greg, and Qiu, Joseph (2020), 'Insurance for economic losses caused by pandemics', *The Geneva Risk and Insurance Review,* 45 (2), 134-70.

Hegger, Dries LT, et al. (2014), 'Assessing stability and dynamics in flood risk governance', *Water Resources Management,* 28 (12), 4127-42.

Herr, Roland (2017), 'Istanbul's infrastructure', *Tunnels & tunnelling international,* 28.

HM-Government (2020), 'Flood and coastal erosion risk management', *Plolicy Statement*.

HMGovernment (2011), 'Climate Resilient Infrastructure: Preparing for a Changing Climate', *Presented to Parliament by the Secretary of State for Environment, Food and Rural Affairs by Command of Her Majesty,* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attac hment_data/file/69269/climate-resilient-infrastructure-full.pdf, (Accessed: 30/08/2022).

Hodgson, Glen (2021), 'The Next Green Bond Wave: Should Ottawa Step In?', *Commentary-CD Howe Institute,* (591), 0_1-22.

Holling, Crawford S (1973), 'Resilience and stability of ecological systems', *Annual review of ecology and systematics,* 4 (1), 1-23.

Holling, Crawford Stanley (1996), 'Engineering resilience versus ecological resilience', *Engineering within ecological constraints,* 31 (1996), 32.

Hyun, Suk, Nishizawa, Toshiro, and Yoshino, Naoyuki (2008), 'Exploring the use of revenue bond for infrastructure financing in Asia', *JBIC Institute Discussion Paper,* (15).

IBRD (2017), 'Pandemic bond prospectus supplement', http://pubdocs.worldbank.org/en/882831509568634367/PEF-Final-Prospectus-PEF.pdf, (Accessed: 20/09/2022).

Ilkisik, O Metin, Ergenc, M Nilay, and Turk, Murat T (2010), 'Istanbul Earthquake Risk and Mitigation Studies', *Disaster Coordination Center, Turkey*, 1-8.

Inderst, Georg (2009), 'Pension fund investment in infrastructure'.

Institute-for-government (2018), 'Funding infrastructure', *Available on:* https://www.instituteforgovernment.org.uk/explainers/funding-infrastructure, (Accessed: 22/09/2022).

Insurance-Information-Institute (2020), 'Background on: Earthquake insurance and risk', *Catastrophes,* file:///Users/y.song/Desktop/final-hd-20210525052712.pdf.

Investment-office (2015), 'Turkey's 'Mega Projects' propel the country towards 2023 targets', *Presidency of the Republic of Turkiye investment office*, https://www.invest.gov.tr/en/news/news-from-turkey/pages/180815-turkey-mega-projects-2023-vision.aspx,(Accessed: 09/09/2022).

Ishfaq, Rafay (2012), 'Resilience through flexibility in transportation operations', *International Journal of Logistics Research and Applications,* 15 (4), 215-29.

Ishfaq, Rafay and Sox, Charles R (2010), 'Intermodal logistics: The interplay of financial, operational and service issues', *Transportation Research Part E: Logistics and Transportation Review,* 46 (6), 926-49.

Istanbul (2018), 'ISTANBUL CLIMATE CHANGE ACTION PLAN summary report'.

Jayaram, Jayanth, Vickery, Shawnee K, and Droge, Cornelia (2000), 'The effects of information system infrastructure and process improvements on supply-chain time performance', *International Journal of Physical Distribution & Logistics Management,* 30 (3/4), 314-30.

Joseph, R, Proverbs, D, and Lamond, J (2014), 'Resilient reinstatement: what can we learn from the 2007 flooding in England', *Flood Recovery, Innovation and Response IV,* 184, 175.

Kamiya, Marco and Zhang, Le-Yin (2016), 'Finance for City Leaders Handbook – Improving Municipal Finance to Deliver Better Services', *United Nations Human Settlements Programme*.

Kara, Mehmet Akif, Taş, Seyhan, and Ada, Serkan (2016), 'The impact of infrastructure expenditure types on regional income in Turkey', *Regional Studies,* 50 (9), 1509-19.

Kaskey, Jack (2018), 'Houston Eyes Designer Bonds to Pay for $15 Billion Ike Dike', *Economics, Bloomberg,* Available at: https://www.bloomberg.com/news/articles/2018-08-30/houston-eyes-designer-bonds-in-quest-for-15-billion-storm-wall, (Accessed: 09/09/2022).

Kaya, Abdullah and Koc, Muammer (2019), 'Over-Agglomeration and its effects on sustainable development: A case study on Istanbul', *Sustainability,* 11 (1), 135.

Kelly, Scott (2015), 'Estimating economic loss from cascading infrastructure failure: a perspective on modelling interdependency', *Infrastructure Complexity,* 2 (1), 1-13.

Koppenjan, Joop FM and Enserink, Bert (2009), 'Public–private partnerships in urban infrastructures: reconciling private sector participation and sustainability', *Public Administration Review,* 69 (2), 284-96.

Kötter, Theo and Friesecke, Frank (2009), 'Developing urban indicators for managing mega cities', *Land Governance in Support of the MDGs: Responding to New Challenges (Washington DC, USA)*, p4.

KPMG (2015), 'Sustainable Insight: Gearing up for green bonds', *KPMG INTERNATIONAL*.

--- (2018), 'Emerging Trends in Infrastructure', *KPMG International,* https://assets.kpmg/content/dam/kpmg/xx/pdf/2018/02/emerging-trends-in-infrastructure.pdf, (Accessed: 19/09/2022).

Kundak, Seda (2017), 'Enhance household resilience in Istanbul', *International Journal of Disaster Resilience in the Built Environment*.

Kunreuther, Howard (2002), 'The role of insurance in managing extreme events: implications for terrorism coverage', *Business economics,* 37 (2), 6.

Kunreuther, Howard C; and Linnerooth-Bayer, Joanne (2003), 'The Financial Management of Catastrophic Flood Risks in Emerging‐Economy Countries', *Risk analysis,* 23 (3), 627-39.

Labbe, Amelie (2017), 'DEAL: world's first pandemic bond', *International Financial Law Review*.

Lamond, Jessica E, Proverbs, DG, and Hammond, FN (2009), 'Accessibility of flood risk insurance in the UK: confusion, competition and complacency', *Journal of Risk Research,* 12 (6), 825-41.

Larsen, Gaia, Christianson, Giulia, and Amerasinghe, Niranjali (2019), 'So Far, Green Bonds Fail to Raise Much Money for Resilience. The Climate Resilience Principles Aim to Change That', *World Resources Institute,* https://www.wri.org/blog/2019/10/so-far-green-bonds-fail-raise-much-money-resilience-climate-resilience-principles-aim, (Accessed: 30/09/2022).

Le Pan, Nicholas (2016), 'Fault Lines: Earthquakes, Insurance, and Systemic Financial Risk', *CD Howe Institute Commentary,* 454.

Lee, Jin-Ping and Yu, Min-Teh (2002), 'Pricing default-risky CAT bonds with moral hazard and basis risk', *Journal of Risk and Insurance*, 25-44.

Leigland, James and Thomas, Rosalind H (1999), 'Municipal bonds as alternatives to PPPs: Facilitating direct municipal access to private capital', *Development Southern Africa,* 16 (4), 729-50.

Li, Xinjun and Wang, Lijie (2015), 'Strategy decision of business interruption insurance and emergency supply strategy based on supply disruptions', *Journal of Industrial Engineering and Management,* 8 (1), 110-21.

Li, Yongjian, et al. (2016), 'Penalty and financial assistance in a supply chain with supply disruption', *Omega,* 61, 167-81.

Liang, Hao and Renneboog, Luc (2020), 'Corporate social responsibility and sustainable finance: A review of the literature', *European Corporate Governance Institute–Finance Working Paper,* (701).

Lichter, Michal, et al. (2011), 'Exploring data-related uncertainties in analyses of land area and population in the “Low-Elevation Coastal Zone”(LECZ)', *Journal of Coastal Research,* 27 (4), 757-68.

Linkov, Igor (2021), *COVID-19: Systemic Risk and Resilience* (Springer Nature).

Linnerooth-Bayer, Joanne and Hochrainer-Stigler, Stefan (2015), 'Financial instruments for disaster risk management and climate change adaptation', *Climatic Change,* 133 (1), 85-100.

LLOYD'S (2019), 'Hidden Vulnerabilities in Supply Chain Risk: A quantitative risk modelling framework', *AIR Worldwide and Lloyd's Report*.

Loh, Hui Shan and Thai, Vinh V (2012), 'The role of ports in supply chain disruption management', *Proceedings of the international forum on shipping, ports and airports. The Hong Kong Polytechnic University, Hong Kong*, 325-37.

Ma, Zong-Gang and Ma, Chao-Qun (2013), 'Pricing catastrophe risk bonds: A mixed approximation method', *Insurance: Mathematics and Economics,* 52 (2), 243-54.

Ma, Zonggang, Ma, Chaoqun, and Xiao, Shisong (2017), 'Pricing zero-coupon catastrophe bonds using EVT with doubly stochastic Poisson arrivals', *Discrete Dynamics in Nature and Society,* 2017.

Maani, Nason and Galea, Sandro (2020), 'COVID‐19 and underinvestment in the public health infrastructure of the United States', *The Milbank Quarterly,* 98 (2), 250.

Mamon, Rogemar S (2004), 'Three ways to solve for bond prices in the Vasicek model', *Advances in Decision Sciences,* 8 (1), 1-14.

Marijnissen, Richard, et al. (2020), 'The Sensitivity of a Dike-Marsh System to Sea-Level Rise—A Model-Based Exploration', *Journal of Marine Science and Engineering,* 8 (1), 42.

McGranahan, Gordon, Balk, Deborah, and Anderson, Bridget (2007), 'The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones', *Environment and urbanization,* 19 (1), 17-37.

Meerow, Sara, Newell, Joshua P, and Stults, Melissa (2016), 'Defining urban resilience: A review', *Landscape and urban planning,* 147, 38-49.

Melikoglu, Mehmet (2013), 'Hydropower in Turkey: Analysis in the view of Vision 2023', *Renewable and Sustainable Energy Reviews,* 25, 503-10.

Mendoza-Tinoco, David, et al. (2017), 'Flood footprint of the 2007 floods in the UK: The case of the Yorkshire and The Humber region', *Journal of Cleaner Production,* 168, 655-67.

Merton, Robert C (1976), 'Option pricing when underlying stock returns are discontinuous', *Journal of financial economics,* 3 (1-2), 125-44.

Mes, Martijn RK and Iacob, Maria-Eugenia (2016), 'Synchromodal transport planning at a logistics service provider', *Logistics and Supply Chain Innovation* (Springer), 23-36.

MetOffice (2020), 'Storm Ciara', https://www.metoffice.gov.uk/weather/warnings-and-advice/uk-storm-centre/storm-ciara, (Accessed: 30/09/2022).

Michel-Kerjan, Erwann and Kunreuther, Howard (2011), 'Redesigning flood insurance', *Science,* 333 (6041), 408-09.

Miller, Ronald E and Blair, Peter D (2009), *Input-output analysis: foundations and extensions* (Cambridge University Press).

Mizutori, Mami (2019), 'Resilient Infrastructure and Disaster Risk Reduction', *United Nations Office for Disaster Risk Reduction (UNDRR) and Centre for Research on the Epidemiology of Disasters (CRED) report.*

Moglia, Magnus, et al. (2021), 'Accelerating a green recovery of cities: Lessons from a scoping review and a proposal for mission-oriented recovery towards post-pandemic urban resilience', *Developments in the Built Environment,* 7, 100052.

Moteff, John D (2012), 'Critical infrastructure resilience: the evolution of policy and programs and issues for congress', (Congressional Research Service Washington, DC).

Motta, Massimo and Peitz, Martin (2020), 'The EU recovery fund: An opportunity for change', *CEPR Policy Portal,* https://voxeu.org/article/eu-recovery-fund-opportunity-change, (Accessed: 15/10/2022).

Muermann, Alexander (2008), 'Market price of insurance risk implied by catastrophe derivatives', *North American Actuarial Journal,* 12 (3), 221-27.

Munich-RE (2017), 'Risks posed by natural disasters', *Munich RE Natural disaster risks,* https://www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards.html, (Accessed: 10/10/2022).

Munnell, Alicia H (1992), 'Policy watch: infrastructure investment and economic growth', *The Journal of Economic Perspectives,* 6 (4), 189-98.

Murray-Tuite, Pamela (2008), 'Evaluation of strategies to increase transportation system resilience to congestion caused by incidents', *Mid-Atlantic University Transportation Center*.

Nema, Pragya, Nema, Sameer, and Roy, Priyanka (2012), 'An overview of global climate changing in current scenario and mitigation action', *Renewable and Sustainable Energy Reviews,* 16 (4), 2329-36.

New-York-Metropolitan (2016), 'CBI 2017 Annual disclosure report', *Climate Bond Standard and Certification Compliance Disclosure*.

Nilsson, Kjell, et al. (2014), 'Strategies for sustainable urban development and urban-rural linkages', *European Journal of Spatial Development*, 25 p.

Nowak, Piotr and Romaniuk, Maciej (2013), 'Pricing and simulations of catastrophe bonds', *Insurance: Mathematics and Economics,* 52 (1), 18-28.

OECD (2015a), 'Green Bond: Mobilising The Debt Cpital Markets for A Low-Carbon Transition', *Bloomberg Philanthropies*.

--- (2015b), 'Fostering Investment in Infrastructure: Lessons learned from OECD Investment Policy Reviews', *OECD Investment Policy Reviews*.

--- (2015c), 'Infrastructure Financing Instruments and Incentives'.

--- (2017), 'Mobilising Bond Markets for a Low-Carbon Transition', *Green Finance and Investment*.

--- (2018), 'Financial Management of Earthquake Risk', https://www.oecd.org/finance/insurance/Financial-management-of-earthquake-risk.pdf, (Accessed: 09/09/2022).

OECD-Data (2022a), 'Long term interest rate', https://data.oecd.org/interest/long-term-interest-rates.htm - indicator-chart, (accessed: 20/08/2022).

--- (2022b), 'Short term interest rate', https://data.oecd.org/interest/short-term-interest-rates.htm - indicator-chart, (Accessed: 20/08/2022).

Orr, Ryan J and Kennedy, Jeremy R (2008), 'Highlights of recent trends in global infrastructure: new players and revised game rules', *Transnational Corporations,* 17 (1), 99-133.

Orsi, Mark J and Santos, Joost R (2009), 'Estimating workforce-related economic impact of a pandemic on the Commonwealth of Virginia', *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans,* 40 (2), 301-05.

Palm, Risa (1995), 'The roepke lecture in economic geography catastrophic earthquake insurance: Patterns of adoption', *Economic Geography,* 71 (2), 119-31.

Pamukcu-Albers, Pinar, et al. (2021), 'Building green infrastructure to enhance urban resilience to climate change and pandemics', (Springer).

Panayiotou, Athena and Medda, Francesca (2014), 'Attracting private sector participation in infrastructure investment: the UK case', *Public Money & Management,* 34 (6), 425-31.

Pant, Raghav, Barker, Kash, and Zobel, Christopher W (2014), 'Static and dynamic metrics of economic resilience for interdependent infrastructure and industry sectors', *Reliability Engineering & System Safety,* 125, 92-102.

Peck, Helen (2005), 'Drivers of supply chain vulnerability: an integrated framework', *International journal of physical distribution & logistics management,* 35 (4), 210-32.

Penning-Rowsell, Edmund C, Priest, Sally, and Johnson, Clare (2014), 'The evolution of UK flood insurance: incremental change over six decades', *International Journal of Water Resources Development,* 30 (4), 694-713.

Pettit, Stephen John and Beresford, Anthony Kenneth Charles (2009), 'Port development: from gateways to logistics hubs', *Maritime Policy & Management,* 36 (3), 253-67.

Pettit, Timothy J, Fiksel, Joseph, and Croxton, Keely L (2010), 'Ensuring supply chain resilience: development of a conceptual framework', *Journal of business logistics,* 31 (1), 1-21.

Picard, Pierre (2008), 'Natural disaster insurance and the equity‐efficiency trade‐off', *Journal of Risk and Insurance,* 75 (1), 17-38.

Plate, Erich J (2002), 'Flood risk and flood management', *Journal of Hydrology,* 267 (1-2), 2-11.

Polacek, Andy (2018), 'Catastrophe bonds: A primer and retrospective', *Chicago Fed Letter,* 405, 1-7.

Poncet, Patrice and Vaugirard, Victor E (2002), 'The pricing of insurance-linked securities under interest rate uncertainty', *The Journal of Risk Finance,* 3 (3), 48-59.

Ponomarov, Serhiy and Holcomb, Mary (2009), 'Understanding the concept of supply chain resilience', *International journal of logistics management,* 20 (1), 124-43.

Posner, Richard A (2004), *Catastrophe: risk and response* (Oxford University Press).

Proverbs, David and Lamond, Jessica (2008), 'The barriers to resilient reinstatement of flood damaged homes', *Proceedings of 4th International i-Rec Conference-Building Resilience: Achieving Effective Post-disaster Reconstruction*.

--- (2017), 'Flood resilient construction and adaptation of buildings', *Oxford Research Encyclopedia of Natural Hazard Science*.

Rajabalinejad, Mohammadreza, et al. (2010), 'Application of the dynamic bounds method in the safety assessment of flood defences, a case study: 17th street flood wall, New Orleans', *Georisk,* 4 (4), 157-73.

Re:Focus (2015), 'LEVERAGING CATASTROPHE BONDS: As a Mechanism for Resilient Infrastructure Project Finance', *RE bound insurance report*.

Rice, James B and Caniato, Federico (2003), 'Building a secure and resilient supply network', *SUPPLY CHAIN MANAGEMENT REVIEW, V. 7, NO. 5 (SEPT./OCT. 2003), P. 22-30: ILL*.

Robson, Alice J (2002), 'Evidence for trends in UK flooding', *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences,* 360 (1796), 1327-43.

Rondinelli, Dennis and Berry, Michael (2000), 'Multimodal transportation, logistics, and the environment: managing interactions in a global economy', *European Management Journal,* 18 (4), 398-410.

Rose, Adam (2004), 'Defining and measuring economic resilience to disasters', *Disaster Prevention and Management: An International Journal*.

Rose, Adam Z (2005), 'Tracing infrastructure interdependence through economic interdependence'.

Saha, Devashree and d'Almeida, Skye (2017), 'Green municipal bonds', *Leaders,* 5 (98), 886.

Santos, Joost R, Orsi, Mark J, and Bond, Erik J (2009), 'Pandemic recovery analysis using the dynamic inoperability input‐output model', *Risk Analysis: An International Journal,* 29 (12), 1743-58.

Santos, Joost R, May, Larissa, and Haimar, Amine El (2013), 'Risk‐based input‐output analysis of influenza epidemic consequences on interdependent workforce sectors', *Risk Analysis,* 33 (9), 1620-35.

Sartzetakis, Eftichios S (2020), 'Green bonds as an instrument to finance low carbon transition', *Economic Change and Restructuring*, 1-25.

Sawant, Rajeev J (2010), 'Emerging market infrastructure project bonds: Their risks and returns', *Journal of Structured Finance,* 15 (4), 75.

Sayers, Paul, et al. (2002), 'Risk assessment of flood and coastal defences for strategic planning (RASP)–a High Level Methodology'.

Sayers, Paul B, Galloway, Gerald E, and Hall, Jim W (2012), 'Robust decision-making under uncertainty–towards adaptive and resilient flood risk management infrastructure', *Flood Risk Planning, Design and Management of Flood Defence Infrastructure. ICE Publishing*, 281-302.

Saygılı, Hülya and Özdemir, K. Azim (2021), 'Regional economic growth in Turkey: the effects of physical, social and financial infrastructure investment', *Empirical Economics,* 60 (4), 2039-61.

Schanze, Jochen (2006), 'Flood risk management–a basic framework', *Flood risk management: hazards, vulnerability and mitigation measures* (Springer), 1-20.

Schelfaut, K, et al. (2011), 'Bringing flood resilience into practice: the FREEMAN project', *Environmental Science & Policy,* 14 (7), 825-33.

Schmitt, Amanda J and Singh, Mahender (2009), 'Quantifying supply chain disruption risk using Monte Carlo and discrete-event simulation', *Simulation Conference (WSC), Proceedings of the 2009 Winter* (IEEE), 1237-48.

Serdaroglu, Tuncay (2020), 'The Relationship Between Public Infrastructure and Economic Growth in Turkey'.

Serdaroğlu, Tuncay (2016), 'The relationship between public infrastructure and economic growth in Turkey', (Ministry of Development, General Directorate of Economic Modelling and …).

Shao, Jia (2015), 'Modelling catastrophe risk bonds', (University of Liverpool).

Shao, Jia, Pantelous, Athanasios, and Papaioannou, Apostolos D (2015), 'Catastrophe risk bonds with applications to earthquakes', *European Actuarial Journal,* 5 (1), 113-38.

Shao, Jia, Papaioannou, Apostolos D, and Pantelous, Athanasios A (2017), 'Pricing and simulating catastrophe risk bonds in a Markov-dependent environment', *Applied Mathematics and Computation,* 309, 68-84.

Sharifi, Ayyoob (2020), 'Urban resilience assessment: Mapping knowledge structure and trends', *Sustainability,* 12 (15), 5918.

Sharifi, Ayyoob and Khavarian-Garmsir, Amir Reza (2020), 'The COVID-19 pandemic: Impacts on cities and major lessons for urban planning, design, and management', *Science of The Total Environment*, 142391.

Siemes, Rutger WA, et al. (2020), 'Artificial Structures Steer Morphological Development of Salt Marshes: A Model Study', *Journal of Marine Science and Engineering,* 8 (5), 326.

Siu, Tak Kuen (2010), 'Bond pricing under a Markovian regime-switching jump-augmented Vasicek model via stochastic flows', *Applied Mathematics and Computation,* 216 (11), 3184-90.

Statista (2021a), 'Major reasons why infrastructure projects fail to proceed according to global professionals as of 2018', https://www.statista.com/statistics/861879/major-failure-reasons-of-infrastructure-projects/,(Accessed: 29/09/2022).

--- (2021b), 'Economic loss from natural disaster events globally from 2000 to 2020', https://www.statista.com/statistics/510894/natural-disasters-globally-and-economic-losses/,(Accessed: 15/10/2022).

SteadieSeifi, M, et al. (2014), 'Multimodal freight transportation planning: A literature review', *European journal of operational research,* 233 (1), 1-15.

Steenbergen, HMGM, et al. (2004), 'Reliability analysis of flood defence systems', *Heron, 49 (1)*.

Stein, Felix and Sridhar, Devi (2017), 'Health as a “global public good”: creating a market for pandemic risk', *bmj,* 358, j3397.

Stevens, Andrew J, Clarke, Derek, and Nicholls, Robert J (2016), 'Trends in reported flooding in the UK: 1884–2013', *Hydrological Sciences Journal,* 61 (1), 50-63.

SwissRe (2013), 'Swiss Reinsurance Company Ltd ', *Swiss Re Catastrophe Bond Prospectus*.

--- (2016), 'SCF Forum: Disaster Risk Finance Insurance incl. Cat and Resilience Bonds', *Swiss Re Global Partnerships*.

--- (2018a), 'Risky cities: earthquake resilience in Istanbul', *Mitigating climate risk,* https://www.swissre.com/risk-knowledge/mitigating-climate-risk/risky-cities-istanbul.html.

--- (2018b), 'Natural catastrophes and man-made disasters in 2017: a year of record-breaking losses', *Swiss Re Institute Sigma,* No.1

Szmigiera, M. (2021), 'Impact of the coronavirus pandemic on the global economy ', *Statistics & Facts,* https://www.statista.com/topics/6139/covid-19-impact-on-the-global-economy/.

Tang, Dragon Yongjun and Zhang, Yupu (2020), 'Do shareholders benefit from green bonds?', *Journal of Corporate Finance,* 61, 101427.

Tao, XX and Tao, ZR (2005), 'Financial instruments integrated with engineering risk assessment for earthquake disaster reduction', *WIT Transactions on The Built Environment,* 82.

Tekeli‐Yeşil, Sıdıka, et al. (2010), 'Factors motivating individuals to take precautionary action for an expected earthquake in Istanbul', *Risk Analysis: An International Journal,* 30 (8), 1181-95.

Tolliver, Clarence, Keeley, Alexander Ryota, and Managi, Shunsuke (2020), 'Policy targets behind green bonds for renewable energy: Do climate commitments matter?', *Technological Forecasting and Social Change,* 157, 120051.

Tomlin, Brian (2006), 'On the value of mitigation and contingency strategies for managing supply chain disruption risks', *Management Science,* 52 (5), 639-57.

Torre-Enciso, Isabel Martinez and Laye, John E (2001), 'Financing catastrophe risk in the capital markets', *International Journal of Emergency Management,* 1 (1), 61-69.

UNCDF (2020), 'Building Urban Economic Resilience during and after COVID-19', *UN-HABITAT for a better urban future,* https://urbanresiliencehub.org/wp-content/uploads/2020/12/WEBSITE-version-DA-13-Training-content-2.pdf, (Accessed: 15/10/2022).

United-Nations (2002), 'Commercial Development of Regional Ports as Logistics Centres', *ECONOMIC AND SOCIAL COMMISION FOR ASIA AND THE PACIFIC, UNITED NATIONS PUBLICATION*.

--- (2017), 'The Paris Agreement', *United Nations Climate Change,* https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, (Accessed: 10/10/2022).

--- (2021), 'Sustainable transport', *Department of Economic and Social Affairs: Sustainable Development,* https://sdgs.un.org/topics/sustainable-transport, (Accessed: 12/10/2022).

Üstün, Abdullah Korkut (2016), 'Evaluating İstanbul’s disaster resilience capacity by data envelopment analysis', *Natural hazards,* 80 (3), 1603-23.

Vaijhala, Shalini and Rhodes, James (2018), 'Resilience Bonds: a business-model for resilient infrastructure', *Field Actions Science Reports. The journal of field actions,* (Special Issue 18), 58-63.

Vallejo, Lola and Mullan, Michael (2017), 'Climate-resilient infrastructure: Getting the policies right'.

Vasicek, Oldrich (1977), 'An equilibrium characterization of the term structure', *Journal of financial economics,* 5 (2), 177-88.

Vaugirard, Victor E (2003), 'Pricing catastrophe bonds by an arbitrage approach', *The Quarterly Review of Economics and Finance,* 43 (1), 119-32.

Vedenov, Dmitry V, Epperson, James E, and Barnett, Barry J (2006), 'Designing catastrophe bonds to securitize systemic risks in agriculture: the case of Georgia cotton', *Journal of Agricultural and Resource Economics*, 318-38.

Wallstreetmojo and Vaidya, Dheeraj (2022), 'Bonds', https://www.wallstreetmojo.com/bonds/, (Accessed:12/08/2022).

Warren, Matthew and Hutchinson, William (2000), 'Cyber attacks against supply chain management systems: a short note', *International Journal of Physical Distribution & Logistics Management,* 30 (7/8), 710-16.

Waters, C Donald J (2003), *Global logistics and distribution planning: strategies for management* (Kogan Page Publishers).

Wheater, Howard S (2006), 'Flood hazard and management: a UK perspective', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 364 (1845), 2135-45.

Willis (2015), 'Willis Capital Markets & Advisory ILS Glossary', *Available at:* https://www.willis.com/Client_Solutions/Services/WCMA/ILS_Glossary/ILS_Glossary.pdf, (Accessed: 29/08/2022).

Wölfel, Roman, et al. (2020), 'Virological assessment of hospitalized patients with COVID-2019', *Nature*, 1-10.

Woo, Gordon (2004), 'A catastrophe bond niche: multiple event risk', *meeting of the NBER Insurance Project Group*.

World-Bank (2017), 'World Bank Launches First-Ever Pandemic Bonds to Support $500 Million Pandemic Emergency Financing Facility', https://www.worldbank.org/en/news/press-release/2017/06/28/world-bank-launches-first-ever-pandemic-bonds-to-support-500-million-pandemic-emergency-financing-facility, (Accessed: 01/10/2022).

--- (2020), 'Global economic prospects, June 2020', (The World Bank).

World-Economic-Forum (2011), 'Global Risks 2011 Sixth Edition An innitiative of the Risk Response Network', *WORLD ECONOMIC FORUM*.

Wu, Desheng and Zhou, Yingying (2010), 'Catastrophe bond and risk modeling: a review and calibration using Chinese earthquake loss data', *Human and Ecological Risk Assessment,* 16 (3), 510-23.

Wu, Teresa, Blackhurst, J, and O'grady, P (2007), 'Methodology for supply chain disruption analysis', *International Journal of Production Research,* 45 (7), 1665-82.

Yamada, Tadashi, et al. (2009), 'Designing multimodal freight transport networks: A heuristic approach and applications', *Transportation science,* 43 (2), 129-43.

Yamagata, Yoshiki and Sharifi, Ayyoob (2018), 'Resilience-oriented urban planning', *Lecture Notes in Energy,* (65).

Young, Virginia R (2004), 'Pricing in an incomplete market with an affine term structure', *Mathematical Finance,* 14 (3), 359-81.

Yucemen, MS (2005), 'Probabilistic assessment of earthquake insurance rates for Turkey', *Natural Hazards,* 35 (2), 291-313.

Zanjani, George (2002), 'Pricing and capital allocation in catastrophe insurance', *Journal of Financial Economics,* 65 (2), 283-305.

Zeytun, S and Gupta, A (2007), 'A Comparative Study of the Vasicek and the CIR Model of the Short Rate'.

Zhang, WenJun (2012), *Computational Ecology: Graphs, Networks and Agent-based Modeling* (World Scientific).

Zimbidis, Alexandros A, Frangos, Nickolaos E, and Pantelous, Athanasios A (2007), 'Modeling earthquake risk via extreme value theory and pricing the respective catastrophe bonds', *ASTIN Bulletin: The Journal of the IAA,* 37 (1), 163-83.

Zsidisin, George A, Melnyk, Steven A, and Ragatz, Gary L (2005), 'An institutional theory perspective of business continuity planning for purchasing and supply management', *International journal of production research,* 43 (16), 3401-20.

ZURICH (2016), 'SUPPLY CHAIN RESILIENCE REPORT', *Business Continuity Institute*