ABSTRACT

Title of Dissertation: URBAN HAZARDS RISK ASSESSMENT: CREATING SUSTAINABLE AND RESILIENT CITIES

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The impact of natural hazards on buildings' long-term environmental performance has gained the attention of the building industry as a result of the increasing environmental loss due to hazard events devastating the built environment around the world. This study explores the role of natural hazards in the perspective of building long-term environmental performance, as well as the environmental value of hazard mitigation. Accordingly, we propose an innovative Life Cycle Assessment (LCA) framework that can incorporate building damage due to hazards and converting this data into quantifiable environmental metrics. Moreover, by incorporating buildings' environmental impacts attributable to hazards as derived from the LCA framework, we arrive at a Benefit-Cost Analysis (BCA) to justify the environmental desirability of hazard mitigation actions. Two case studies are presented: the first one assesses the environmental performance of a single reinforced concrete building under seismic risk; the second assesses the environmental justification for seismic retrofit on a region scale. The results show that, while the expected environmental loss caused by natural hazards is significant, such loss can be effectively reduced by pre-event mitigation; and that the benefits, in terms of reduction in environmental loss, outweigh the environmental impact of the mitigation itself. It is hoped that this study will serve as a basis for further research aimed at assessing the sustainability of constructed facilities facing natural hazards, and evaluating the environmental value of hazard-mitigation strategies.

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by

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Chapter 1: Introduction

Substantial damage to existing buildings and other structures resulting from natural hazards has recently increased due to various factors, such as the climate change and rapid urbanization. The impact of natural hazards on buildings' long-term performance has gained the attention of the building industry as a result of the increasing loss due to hazard events devastating the built environment around the world. As a result, the words "sustainability" and "resilience" are dominating research trends and practical interests in the field of natural disaster management in the built environment. Sustainable development aims to improve the quality of life for present and future generations, in the areas of society, economy, and environment. Resilience represents the conditions of a social system, resulting from physical, social, economic, and environmental factors, in terms of their capacity to cope with, and recover from the impact of hazards.

This dissertation investigates and assesses the performances of both sustainability and resilience of a city under natural hazards. In this chapter, subsection 1.1 presents background information about the importance of sustainability performance of constructed assets in natural hazards and how it can be assessed. Subsection 1.2 describes the importance of the concept of integration of physical vulnerability, system and social resilience in disaster management science. Subsection 1.3 shows the organization of the proposed dissertation.

1.1 Sustainability Performance of Constructed Facilities under Natural Hazards

1.1.1 Problem Statement

Sustainable development aims to improve the quality of life for present and future generations, in the areas of society, economy, and environment – also known as the triple-bottom-line of sustainability (GBC, 2009). To comprehensively improve the long-term sustainability of a building, a balance between social, economic and environmental performance must be achieved over its entire life-cycle. Yet, the majority of previous studies of buildings' sustainability performance vis-à-vis disaster risk have ignored environmental impact, instead emphasizing either social impacts, e.g. the number of fatalities, displaced households or shelter requirements (Tantala et al., 2008); (Rein and Corotis, 2013), or economic ones, such as the cost of repairs or business disruption (FEMA, 2008); (Remo and Pinter, 2012, Rein and Corotis, 2013). The reason that environmental performance is given less attention than the other two factors may lie in the lack of well-defined criteria and methods for measuring it (Wei et al., 2015). Although still limited in number, discussions of the environmental impact of natural disasters upon buildings have recently come to greater prominence, as the energy demands associated with post-event recovery continue to grow (Padgett and Tapia, 2013, Hossain and Gencturk, 2014, Feese et al., 2014, Wei et al., 2015). The environmental impacts arising from disaster recovery have also been proposed as performance metrics, as part of both seismic design criteria (FEMA, 2006b); (Hamburger et al., 2012) and sustainability rating systems (Comber and Poland, 2013). Nevertheless, only a handful of recent studies have specifically examined all three dimensions of the sustainability performance of infrastructure (Dong et al., 2013), and there seem to be no studies at all that simultaneously address all three aspects of sustainability of a building exposed to natural-disaster risk. This represents a very serious gap in the literature, which might lead to over- or under-estimation of the value of hazard-resistant designs.

1.1.2 Research Objectives

This study aims to answer the research questions as described in the above problem statement by achieving the following objectives: (1) develop a methodology that can translate seismic building damage into clearly quantifiable social, economic and environmental impacts, taking into account the use of various repair methods appropriate to each damage state as well as local economic/environmental data; (2) propose a Life-cycle Assessment (LCA) framework that can evaluate the long-term costs and benefits of seismic retrofit designs; and (3) conduct a risk-based CBA to assess the sustainability value of two retrofit designs, taking into consideration the uncertainty associated with seismic events. It is hoped that the present research will serve as a basis for further studies of the long-term sustainability of performance-based designs (new or retrofit) for buildings confronting natural hazards, with the wider aim of achieving optimal cost-effective designs.

1.1.3 Research Methodology

A thorough literature review of sustainable performance of built assets in natural hazards is provided. Also, the Life-cycle Assessment (LCA) method is studied closely. In addition, studies regrading risk-based Cost-benefit Analysis in the field of natural disaster management are discussed. A LCA framework for assessing the sustainability performance of buildings exposed to natural hazards is developed. The purpose of the proposed LCA framework is to assess the life-cycle sustainability performance of buildings at risk from seismic events. This performance is evaluated and represented in terms of social, economic, and environmental metrics.

1.2 Risk of an Urban Area under Natural Hazards

1.2.1 Problem Statement

Destruction of modern built environments resulting from natural disasters has recently increased due to the repercussions of climate change as well as human-related activities, such as rapid population growth, urbanization in hazard-prone areas. Reduction of urban natural disaster risk has become major global concern for the sustainable development of urban areas. Accordingly, several risk assessment tools have been developed for evaluating and identifying the level of risk and thus according risk reduction plans can be made and their effectiveness can be assessed. Traditionally, research on natural disaster risk assessment has been divided into two major distinct approaches: engineering-based and social science-based (Brink and Davidson, 2014). With advanced understanding of underlying physical mechanisms controlling the behavior of natural hazards, as well as failure mechanisms of physical vulnerability of built assets subjected to natural hazards, engineering-based approaches have focused on damage of constructed facilities and estimation of direct loss during disasters. On the other hands, arguing that the risk of society under hazards is not solely dominated by the interaction of hazards and built environment, social science-based studies have attempted to investigate the social vulnerability/resilience of a community or city to hazards – capacities of exposed people and communities to copy with and recovery from losses. Nevertheless, due to the complex multifaceted nature of social vulnerability, questions still remain as to standard guidelines for quantifying social resilience to meaningful and operational metrics for evaluating the effectiveness of practical risk reduction decision. Overall, neither engineering-based, nor social science-based approach can comprehensively evaluate the disaster risk of a community, insofar as either one of them can only explain the effects of vulnerability of an element at risk from a narrow specific point of view.

Attempting to comprehensively assess the multifaceted vulnerability and resilience of an urban system, with the expectation of development of an operational tool for risk control decision-making support, mainly two areas have promoted in the disaster risk management community: (1) conceptual frameworks for comprehensively capturing and assessing vulnerability and resilience; and (2) methodologies to integrate multifaceted vulnerability and resilience for an operational metric in risk management practice. Working on the former has led to awareness of variety of factors on the extent of natural disaster risk, including physical factors such as potential intensity, and frequency of future hazard events, resistance to hazards of buildings, and social factors such as wealth, and health conditions of exposed people. On the other hand, studies in the second area have aimed to determine operational metrics for the purpose of risk identification and communication in risk reduction decision-making support. The majority of such studies have widely employed an single index or score (Kleinosky et al., 2007), which is always composed of various factors with different units, to identify the relatively risky areas where risk reduction action needs to be performed. In addition, rather than aggregating different factors into a single index, some studies have also examined spatial relationship between these factors. For instance, they superimposed social and physical vulnerability on a same map to highlight the spatial relationship among social and physical factors (Dewan, 2013) (Felsenstein and Lichter, 2014) (Koks et al., 2015). Nevertheless, although operational, either the use of index, or of spatial correlation, cannot severe as a meaningful metric for risk reduction action decision-making support.

Summarizing previous related studies, one can conclude that the challenge of the application of a holistic risk assessment model to risk management practice refers to following two major aspects, which is also the problem statement guiding the proposed study.

1. Distinguish and integrate multifaceted components of vulnerability and resilience to natural hazards

This refers to the various terms that have been taken into consideration as the components of vulnerability in most current natural risk disaster studies, such as vulnerability, susceptibility, coping capacity and resilience. Accordingly, the following research questions are addressed:

(a) How the physical vulnerability, system resilience, and social resilience can be distinguished from one another?

(b) How the physical vulnerability, system resilience, and social resilience can be linked in accordance with temporal and spatial scales?

2. Apply multifaceted components of vulnerability and resilience to the practice of risk mitigation

This refers to meaningful and operational metrics or tools that can be used to identify and compare degree of risk for the choice of effective risk reduction action. Accordingly, the following research questions are addressed:

(c) How the physical vulnerability, system resilience, and social resilience can be incorporated into practice of disaster risk management policy in correspondence with different phases of disaster management cycle?

1.2.2 Research Objectives

This study aims to answer the research questions as described in the above problem statement by achieving the following objectives: 1) develop a comprehensive framework for assessment of natural disaster risk by integrating physical impacts, system resilience and social resilience of an urban area; and 2) introduce a methodology that can identify relatively risky area at community level by means of capturing the interaction between physical impact and socio/system resilience. Following the development of framework, a case study is conducted to illustrate the application of the proposed methodology to the evaluation of the seismic risk in an urban area, and to the determination of corresponding risk reduction actions. The present methodology is hoped to serve as a basis for further studies aimed at assessing urban natural disaster risk, and determining effective hazard-mitigation strategies.

1.2.3 Research Methodology

A thorough literature review of risk assessment of built facilities and social unit in natural hazards is provided. Also, the studies regrading vulnerability and resilience assessment is closely discussed. In addition, studies regrading risk assessment in the field of natural disaster management are discussed. A novel framework for assessing the vulnerability of a city exposed to natural hazards is developed. The purpose of the proposed framework is to assess physical vulnerability, system resilience and social resilience of a city under natural hazards risk. Finally, risk concentration indexes are introduced to serve as metric that can integrate various components of vulnerability servicing as a meaningful and operational for the risk reduction decision-making support.

1.3 Dissertation Organization

This study is divided into four parts. Following the introduction of the study in chapter 1 where the research background and problem statement are identified, chapter 2 discusses the first introduces a methodology that can translate seismic building damage into clearly quantifiable social, economic and environmental impacts, which can be used when selecting repair methods appropriate to various states of building damage and to the local economic and environmental situation. We also propose a life-cycle assessment framework that can evaluate the costs and benefits associated with a seismic design over a building's life-cycle. Two case studies are presented: the first assesses the sustainability performance of a single reinforced-concrete building under seismic risk. The second, taking into account the uncertainty associated with seismic events, comprises a risk-based cost-benefit analysis of the desirability, in terms of the three sustainability metrics, of two seismic retrofit designs on a regional scale. Chapter 3 first thoroughly reviewed both engineering-based and social science-based approaches for assessment of natural hazards risk of urban areas. We developed a comprehensive framework for assessment of natural disaster risk by integrating physical impacts, system resilience and social resilience of an urban area. Also we introduced a methodology that can identify relatively risky area at community level by means of capturing the interaction between physical impact and socio/system resilience. The proposed methodology was finally illustrated by a case study in the city of Tiberias for assessing its seismic risk. Finally, the contributions, potential practical applications, and limitations of the proposed methodology are summarized in chapter 4.

Chapter 2: Assessment of Sustainability Performance of Buildings Subjected to Natural Hazards

2.1 Abstract

A complete sustainable-performance analysis that takes into consideration the whole of the triple-bottom-line of sustainability is necessary when one needs to balance social, economic and environmental impacts in an optimal cost-effective design based fundamentally on sustainability performance objectives. This chapter introduces a methodology that can translate seismic building damage into clearly quantifiable social, economic and environmental impacts, which can be used when selecting repair methods appropriate to various states of building damage and to the local economic and environmental situation. This dissertation also propose a life-cycle assessment framework that can evaluate the costs and benefits associated with a seismic design over a building's life-cycle. Two case studies are presented: the first assesses the sustainability performance of a single reinforced-concrete building under seismic risk. The second, taking into account the uncertainty associated with seismic events, comprises a risk-based cost-benefit analysis of the desirability, in terms of the three sustainability metrics (separately and in combination), of two seismic retrofit designs on a regional scale. A comparison of the relative merits of the two proposed retrofit designs reveals that preventing buildings from becoming

irreparably damaged plays an important role in increasing the cost-efficiency of a retrofit design. Our findings also indicate that, while neither design could be considered feasible with respect to the three sustainability metrics individually, the lower-cost/lower-resistance design is justifiable if measured by the combined benefit from all three metrics, expressed in monetary terms. This finding emphasizes the necessity of a complete sustainable-performance analysis in achieving a cost-effective design. Finally, when comparing all three metrics in monetary terms, the savings associated with the reduction in fatalities contribute the most to the total expected benefit of a retrofit project, followed by reduced repair costs and reduced CO2 emissions.

2.2 Introduction

Growing awareness of the impacts of greenhouse gases (GHG) on adverse climate change has prompted efforts by energy-intensive industries to develop various emission-calculation tools for assessing and controlling GHG magnitude. The significant level of GHG emissions attributable to buildings – which are responsible for 40% of the annual energy consumption in the U.S (DOE, 2011) – has motivated the building industry to develop sustainable solutions for reducing this harmful environmental impact (Kandil et al., 2012). Evaluation of the lifetime environmental performance of a building involves taking into account numerous types of equipment and techniques and enormous quantities of materials. Accordingly, Life Cycle Assessment (LCA) has emerged as a useful tool for assessing the environmental impact of buildings, due to its ability to measure both direct and indirect lifetime energy consumption associated with products and processes (Rebitzer et al., 2004). Several LCA models have been developed to assess the environmental impact of construction and operation activities throughout a building's life cycle. Recently, in addition to the environmental impact of the aforementioned conventional activities, the impact of natural hazards and their associated recovery activities has also come under scrutiny. Researchers have attempted to incorporate natural disaster risks into traditional building LCA models, for example, to assess the environmental impact of post-disaster rehabilitation, which always involves high energy consumption. After the 2011 Great East Japan Earthquake, which damaged or destroyed 1.12 million buildings, building-rehabilitation-related activities in the affected region were estimated to have generated 26.3 million tons of CO2-equivalent emissions: an amount equal to 2.1% of the total GHG emissions of Japan in 2010 (Pan et al., 2014). Thus, to achieve the goal of sustainable development in the building industry, it will be necessary to incorporate natural disaster risks into the environmental assessment of buildings' life cycles. Additionally, as a practical alternative for enhancing buildings' hazard resilience, the potential role of hazard mitigation in sustainability-driven building improvements is also worthy of investigation.

Traditionally, energy consumption in a building’s life cycle has been divided into two distinct phases: embodied and operational energy; several LCA studies of building sustainability have aimed to determine the sources of environmental impacts, and to measure these impacts within these two conventional life cycle phases (Cabeza et al., 2014). Researchers have also investigated various approaches to saving embodied and operational energy (Ramesh et al., 2010)). However, amid the increasing environmental loss due to hazard events devastating the built environment around the world, aforementioned conventional LCA frameworks have become partially obsolete, insofar as they cannot accurately assess the environmental performance of buildings in the face of natural disasters. Moreover, failing to incorporate natural disaster risk into LCA frameworks can lead to overestimates of buildings’ lifetime sustainability, due to the major environmental impact that may result from post-disaster rehabilitation. LCA frameworks that take into consideration of the hazard resilience’s role can more accurately evaluate the long-term sustainability of buildings that are potentially subject to disastrous events. With this in mind, researchers have recently conducted several LCA studies of the effects of structural hazard vulnerability on buildings’ lifetime sustainability, focusing particularly on different structural types (Menna et al., 2013), seismic design load (Arroyo et al., 2012); (Feese et al., 2014); (Hossain and Gencturk, 2014) and seismic-resistant systems (Sarkisian, 2014). The environmental impacts arising from post-hazard rehabilitation have also been proposed as performance metrics in seismic design criteria (FEMA, 2006b); (Hamburger et al., 2012) and sustainability rating systems (Comber and Poland, 2013). Taken as a whole, the evidence from previous studies implies that a building with higher hazard resilience consumes more initial embodied energy in exchange for lower energy requirements arising from rehabilitation. Yet, while aforementioned studies have determined the benefits of enhancing hazard resilience in terms of reduced environmental impact from rehabilitation, neither the upfront “cost” (in terms of the additional impact from more robust construction) nor the “net benefit” of these structural enhancements have been fully investigated. Therefore, the tradeoff between structural resilience and sustainability design must be more fully explored if we are to accurately assess the value of structural enhancement vis-à-vis buildings’ long-term environmental sustainability.

Structural retrofitting is one practical pre-event option for reducing building damage in earthquakes. In one of just a handful of relevant studies of this topic, Padgett and Tapia (Padgett and Tapia, 2013) specifically examined the effects of hazard mitigation on a regional bridge portfolio’s lifetime environmental performance. They argue that a thoroughly risk-based Benefit-Cost Analysis (BCA) can be used to answer the question of whether the negative environmental impact mitigated by retrofitting outweighs the expenditures for the retrofit itself. A risk-based BCA can be seen as a process of calculating the sustainable benefit and cost associated with mitigation through a comprehensive LCA framework that takes into account the risk to the designated built environment. Therefore, with the intention of discovering the role of seismic risk mitigation through structural retrofit on buildings’ lifetime sustainability on a regional scale, this study aims to (1) develop a comprehensive LCA framework that can incorporate building damage and convert this data into quantifiable environmental impact by means of capturing the main sources of the impact during both pre-seismic structural retrofitting and post-seismic rehabilitation; (2) evaluate the environmental value of hazard mitigation by conducting a risk-based BCA focused on building lifetime sustainability; and (3) develop a methodology that can translate seismic building damage into clearly quantifiable social, economic and environmental impacts, taking into account the use of various repair methods appropriate to each damage state as well as local economic/environmental data. It is hoped that the present research will serve as a basis for further studies of the long-term sustainability of performance-based designs (new or retrofit) for buildings confronting natural hazards, with the wider aim of achieving optimal cost-effective designs.

2.3 Literature Review

2.3.1 Life Cycle Assessment (LCA) of Building Sustainability

LCA methodology has been widely adopted, due to its proven capacity to capture the direct and indirect consumption of energy and natural resources, for assessing buildings' lifetime environmental performance. Generally, the entire life cycle of a building can be divided into two phases: embodied and operational energy (Ramesh et al., 2010); (Cabeza et al., 2014). Embodied energy includes the energy that is consumed in all activities involved in building construction, including the manufacture and transportation of materials, technical installations of components, and construction-related waste disposal. Operational energy includes the energy required for maintenance of HVAC systems, water, lighting, and so forth. Several LCA studies of building sustainability have been carried out to identify the environmental impacts, such as energy use or GHG emissions, in these two life cycle phases. In most of this literature, although results vary along with the investigated parameters (e.g. building types, supply systems, locations, lifespan, and so forth), operational energy has been found to consume the lion's share of total life cycle energy: up to 90%, as against 20% in average for embodied energy (Ramesh et al., 2010); (Cabeza et al., 2014). Meanwhile, studies have focused on the opportunities to reduce the energy consumption within these two phases. Several green technologies and systems have been developed for reducing operational energy: for example, Citherlet and Defaux (Citherlet and Defaux, 2007) noted that improvements to insulation systems, as well as the use of renewable energy, significantly reduce operational energy consumption, while Gustavsson and Joelsson (Gustavsson and Joelsson, 2010) determined that the choice of energy supply systems plays an important role in optimizing operational energy. Moving beyond technical approaches to buildings per se, changes in occupants' energy-use behaviors have been found to be an economically efficient alternative in saving operational energy (Chen et al., 2012).

Compared with operational energy , opportunities for reductions in embodied energy have also been investigated, although generally these account for lower impacts on life cycle energy (Treloar et al., 2001); (Langston and Langston, 2008). Nevertheless, because the current trend in the industry is toward ever more effective reining in operational energy via a variety of advanced approaches, the share of embodied energy is expected to continue to grow, until it eventually reaches nearly 100% of the total life cycle energy required by net-zero operational energy buildings (Nässén et al., 2007). Various researchers have investigated the potential for reducing embodied energy through the selection of environmentally efficient materials and less energy-intensive construction techniques and equipment (Wong et al., 2013). Several studies have shown that the off-site manufacturing of building materials is responsible for 75%-90% of total embodied energy (Scheuer et al., 2003); (Zabalza Bribián et al., 2009); (Yan et al., 2010), and that this material production energy has been continuously increasing due to the current trend of using energy-intensive materials (Langston and Langston, 2008). As a result, the use of environmentally friendly materials, such as low-energy and reclaimed materials, has been widely investigated and found to be a major opportunity for reducing embodied energy (Venkatarama Reddy and Jagadish, 2003); (Blengini, 2009); (Yan et al., 2010). The choice of construction equipment can also help minimize the energy consumed in construction (Waris et al., 2014); (Hasan et al., 2013). Reviewing the available LCA literature on buildings' environmental performance (Khasreen et al., 2009); (Ramesh et al., 2010); (Sharma et al., 2011); (Cabeza et al., 2014), one can conclude that the majority of current studies focus on the environmental impacts associated with either the construction or operation phase; as such, the lack of investigation of the additional impact associated with rehabilitation due to natural disasters represents a significant gap in the literature. Failure to consider the effects of natural disasters and disaster remediation may lead to overestimations of buildings' long-term environmental performance.

2.3.2 Incorporating Natural Hazard Risk into Building Life Cycle Environmental Performance

Recently, destruction of modern built environments resulting from natural disasters has increased due to the repercussions of climate change and rapid urbanization in hazard-prone areas (Li et al., 2011). These events cause not only major social and economic losses, but also significant environmental impacts due to the large amounts of energy consumed and emissions generated during post-disaster recovery activities: debris removal and disposal, the demolition and repair of damaged buildings. The term sustainability encompasses three interdependent factors: society, economy, and environment (also known as the triple-bottom-line of sustainability) (GBC, 2009). Therefore, a complete LCA of building sustainability requires taking all three of these elements into account over a building’s entire lifespan (Hossain and Gencturk, 2014). Yet, the majority of previous studies of building sustainability vis-à-vis disaster risk have strongly emphasized either social impacts, e.g. the number of casualties, displaced households or shelter requirements (Tantala et al., 2008); (Rein and Corotis, 2013), or economic ones: the cost of repairs or business disruption (FEMA, 2008). Although still limited in number, discussions of the environmental impact of natural disasters have recently gained prominence as the energy demand associated with post-event recovery activities continues to grow. Most of these efforts have focused on seismic hazards because, compared to other types of natural disaster, earthquakes generally tend to cause the more severe damage to building structures and thus lead to the greatest energy consumption in the aftermath. The U.S. Applied Technology Council (ATC) has stated that one aim of its latest seismic design guide – Next-Generation Building Seismic Performance Assessment Methodology – is intended to provide a framework for addressing the additional environmental impacts associated with recovery from seismic damage, including GHG emissions, energy utilization and solid landfill generation (FEMA, 2012). Since those guidelines appeared, Comber and Poland (Comber and Poland, 2013) developed an LCA model that allows quantification of the environmental effects of implementing them. In their research, a two-story medical building was investigated to determine its environmental performance under both high and normal seismic design criteria. The results indicated that an additional 2% of initial energy investment (in materials that met the higher seismic criteria) yielded a 9% net decrease in total lifetime environmental impacts in terms of CO2 emission. Menna et al. (Menna et al., 2013) performed a risk-based LCA to quantify the expected environmental impact related to a building's seismic resilience, in which a generic five-story reinforced concrete (RC) structure was investigated for its environmental performance in designated earthquakes over a period of 100 years. Their results showed that the environmental impact attributable to the earthquake-related restoration of the building was equal to 25% of its embodied energy. Arroyo et al. (Arroyo et al., 2012) introduced environmental losses into the seismic design process, and suggested that increasing the design load could help limit environmental emissions caused by the repair of future seismic damage. Sarkisian (Sarkisian, 2014) investigated enhanced seismic systems' ability to reduce carbon gas (CO2) emission resulting from post-earthquake reconstruction, and found that the design of a seismic isolation system for a 13-story steel structure in California could reduce that building's lifetime CO2 emissions by 15% over its 25-year service life. Hossain and Gencturk (Hossain and Gencturk, 2014) converted structural seismic damage into quantifiable environmental impacts, and concluded that the impact from post-seismic repair activities was considerably greater for low-performance designs than for high-performance ones. Feese et al. (Feese et al., 2014) integrated seismic risk analysis for building damage into an LCA framework, as a means of quantifying the environmental performance associated with different design code levels under earthquake conditions. The results showed that upgrading the design code can reduce environmental impacts, with the savings being achieved during the recovery of damaged buildings.

Taken as a whole, the evidence from the aforementioned studies implies that pre-event enhancement of structural performance can help reduce the environmental impact of post-event remediation of building damage. However, the environmental tradeoff between structural enhancement and the reduction of post-disaster environmental impact of buildings has yet been conclusively investigated through a comprehensive LCA framework that can capture the main sources of environmental impacts arising from both retrofitting and post-event rehabilitation. Table 2.1 summarizes the earthquake rehabilitation activities that were investigated as to their environmental impacts in previous relevant studies. Clearly, most of them only focused on impact due to repair. Ranging from the equivalent of 9% to 30% of the embodied energy of the investigated buildings, repair is indeed a major contributor to the total environmental impacts of rehabilitation. Nonetheless, discussion of the impacts from other rehabilitation activities, such as disaster debris disposal and demolition of damaged components, can only be found in a few studies, despite the fact that the impact associated with removing, demolishing, and discarding damaged components was estimated as equivalent to 15% of embodied energy (Chiu, 2012). Moreover, the impact due to debris disposal alone can reach approximately 42% of the total energy consumption of rehabilitation in some cases (Pan et al., 2014). Therefore, in addition to repair, the considerable environmental impacts associated with other rehabilitation activities, including demolition and debris disposal, should be considered if the full environmental impact of rehabilitation is to be accurately assessed. In addition to the aforementioned deficiencies available literature regarding the impacts of natural hazards on building sustainability, most studies have merely discussed the structural performance of particular building types in specific seismic events (usually historical earthquakes), without regard to either the uncertainty surrounding earthquake frequency or the attributes of the local built environment. To properly estimate the expected building damage in potential earthquakes, one should conduct a risk-based seismic damage analysis that takes into consideration of local characteristics of the built environment, such as seismicity, soil conditions and building fragility curves.

Structural retrofit is one practical means for reducing damage from earthquakes, as it can effectively improve an existing building's deficient structural performance. However, much as with the upgrading of seismic design loads, retrofitting work causes up-front environmental impacts that must be weighed against reductions in impact that will occur only if the building is damaged. Inherently, a risk-based BCA can serve as a useful tool to assess the value of mitigation actions with respect to buildings' environmental performance. So far, however, only a handful of studies have specifically examined the role of hazard mitigation on buildings' lifetime sustainability. To justify the environmental value of retrofit actions of low-rise R.C. buildings, Chiu et al. (Chiu, 2012) calculated the CO2 emissions associated with both retrofit and repair work for their expected damage in earthquakes by conducting a risk-based payback period method. However, when evaluating the economic and environmental losses incurred to repair damaged buildings, this study have adopted global repair cost ratios rather than accumulating the total cost of each activity involved in each designated repair method in light of local economic data (e.g. materials, equipment, and labor-force availability and cost). Utilizing a risk-based BCA for structural intervention that takes into account local seismicity and seismic-damage functions of bridges in California, Padgett and Tapia (Padgett and Tapia, 2013) have investigated the cost and benefit in terms of environmental performance through a LCA framework that can capture the main sources of environmental impacts arising from both retrofitting and post-event repair. The results show that by retrofitting a typical single deficient bridge, a reduction in energy use equivalent to 69% of its embodied energy can be achieved during 50 years of its remaining service life, due to reductions in expected seismic repair actions. Additionally, in examining the potential environmental benefits of retrofitting a regional portfolio of bridges, the benefit-cost ratio (BCR) in terms of CO2 emission associated with retrofitting the top 10 unsustainable bridges was found to be greater than one, whereas the BCR of retrofitting all 515 bridges was less than one. This result clearly upheld the merit of risk-based BCA in assessing the environmental performance of at-risk buildings: whether the impacts mitigated by retrofitting can outweigh the expenditures for the retrofit itself depends mainly on the seismic risk of the region, followed by other factors, including the level of strengthening and the expected service life of structures. However, although a good example for examining the environmental value of hazard mitigation is provided in this study through a risk-based BCA using a LCA framework that can capture environmental impacts arising from construction activities, the LCA framework of Padgett and Tapia is specifically designed for bridges. Therefore, to assess the impacts of natural hazards on building sustainability, this dissertation proposes an innovative risk-based BCA methodology, coupled with a comprehensive LCA framework of buildings that can capture the main sources of environmental impact during both pre-seismic structural retrofitting and post-seismic rehabilitation.

Table 2.1. Previous studies' estimates of environmental impacts due to rehabilitation activities

Study	Environmental impacts from rehabilitation activities (% embodied energy)		
	Demolition	*Debris disposal*	*Repair*
Chiu et al. (2013)	✓ (15%)[a]	✓ [a]	✓ (2%-50%)
(Comber and Poland, 2013)			✓ (9%-11%)
(Menna et al., 2013)			✓ (25%)
(Padgett and Tapia, 2013)			✓ (20%)
(Hossain and Gencturk, 2014)			✓ (5%-40%)
(Sarkisian, 2014)			✓ (10-30%)
(Feese et al., 2014)			✓ (29%)[b]
(Pan et al., 2014)		✓ [c]	✓ [c]

Note: the results vary with different investigated parameters, including building types, seismic damage levels, and the materials and equipment involved.

[a] 15% was calculated by combining the impacts from demolition with those from debris disposal.

[b] The percentage was calculated by the present authors based on the information provided in the literature.

[c] The impacts from demolition and debris disposal were statistically estimated to be equivalent to 42% and 58% of the total impacts from rehabilitation, respectively.

2.3.3 Incorporating Natural Hazard Risk into Building Life Cycle Sustainability Performance

Sustainable development aims to improve the quality of life for present and future generations, in the areas of society, economy, and environment – also known as the triple-bottom-line of sustainability (GBC, 2009). To comprehensively improve the long-term sustainability of a building, a balance between social, economic and environmental performance must be achieved over its entire life-cycle. Yet, the majority of previous studies of buildings' sustainability performance vis-à-vis disaster risk have ignored environmental impact, instead emphasizing either social impacts, e.g. the number of fatalities, displaced households or shelter requirements (Tantala et al., 2008); (Rein and Corotis, 2013), or economic ones, such as the cost of repairs or business disruption (FEMA, 2008); (Remo and Pinter, 2012, Rein and Corotis, 2013). The reason that environmental performance is given less attention than the other two factors may lie in the lack of well-defined criteria and methods for measuring it (Wei et al., 2015). Although still limited in number, discussions of the environmental impact of natural disasters upon buildings have recently come to greater prominence, as the energy demands associated with post-event recovery continue to grow (Padgett and Tapia, 2013, Hossain and Gencturk, 2014, Feese et al., 2014, Wei et al., 2015). The environmental impacts arising from disaster recovery have also been proposed as performance metrics, as part of both seismic design criteria (FEMA, 2006b)a; (Hamburger et al., 2012) and sustainability rating systems (Comber and Poland, 2013). Nevertheless, only a handful of recent studies have specifically examined all three dimensions of the sustainability performance of infrastructure (Dong et al., 2013), and there seem to be no studies at all that simultaneously address all three aspects of sustainability of a building exposed to natural-disaster risk. This represents a very serious gap in the literature, which might lead to over- or under-estimation of the value of hazard-resistant designs.

Performance-based seismic design is the process of designing a building with the expectation of assessing its response to future earthquakes and determining whether such response satisfies particular performance objectives (Ghobarah, 2001). Depending on the purposes of the designed facilities, the consequences may be expressed as building damage, casualties, repair costs, and so forth. Since the appearance of guidelines that introduced and defined various specific criteria for measuring performance (FEMA, 2000); (ASCE, 2007), several studies have aimed to optimize the objectives of seismic designs through a performance-based seismic assessment. Liu et al. (Liu et al., 2005), for example, proposed an optimal design methodology for a steel moment-resisting frame based on the criteria of initial construction cost and seismic resistance. Zou et al.'s (Zou et al., 2007) research on seismic upgrades of reinforced-concrete (RC) buildings took different quantities of the retrofitting material (fiber-reinforced polymer) as design variables, and proposed an optimization technique to determine the minimal material cost. Aydin and Boduroglu (Aydin and Boduroglu, 2008) introduced a seismic-retrofit method that identifies the optimal location and size of the cross-section of braces. However, these studies have focused on initial retrofit costs and/or minimizing structural seismic responses, while largely ignoring the earthquake-related costs that may be incurred during buildings' service lives.

When evaluating the cost-efficiency of various retrofit designs based on the long-term performance of a building exposed to seismic risk, a life-cycle cost beyond the initial construction cost should be included, to represent the impact of potential earthquakes that occur during the building's expected life-cycle. In general, a more resistant design with higher initial construction costs will have a lower life-cycle cost due to its more robust seismic resistance to earthquakes, as compared to a cheaper and less robust design. Several studies of performance-based seismic design have estimated life-cycle costs arising from certain seismic events or design demand, and used these to optimize design solutions with multiple performance objectives (Fragiadakis and Papadrakakis, 2008); (Park et al., 2014). In contrast to these scenario-based analyses, a risk-based analysis takes into consideration all potential earthquakes over a specified interval of time along with the probability of their occurrence, and is therefore a more useful basis for projections of building performance in areas of moderate-frequency seismicity (but high vulnerability). The use of risk-based analysis for estimating the life-cycle costs and benefits associated with seismic designs, a technique known as risk-based life-cycle cost-benefit analysis (CBA), has been widely adopted to justify the economic desirability of particular designs. Fragiadakis et al. (Fragiadakis et al., 2006) proposed a methodology for the optimum cost-effective design of steel structures that takes into account the life-cycle costs attributable to the impact of potential future earthquakes. Taflanidis and Beck (Taflanidis and Beck, 2009) introduced a probabilistic framework, including the uncertainties of seismic events as well as structural behavior, for estimating and optimizing the life-cycle cost of passive dissipative devices. Padgett et al. (Padgett et al., 2010) conducted a seismic life-cycle CBA to determine the optimal retrofit measures, from among various designated options, for old bridges located in different areas. The results showed that the most cost-effective retrofit for a particular bridge depends on local seismic intensities and the effectiveness of retrofit at different damage levels. Based on a U.S.-based database of seismic repair cost (ATC (ATC, 1985) and a Taiwanese-based CO2-emission database (Chang et al., 2002), Chiu et al. (Chiu et al., 2013) evaluated the environmental as well as economic benefits of seismic retrofit investments in RC buildings in Taiwan and found that return on these investments was both environmentally and economically positive.

However, when evaluating the economic and/or environmental losses incurred to repair damaged buildings, many studies have adopted global repair cost ratios (Ghosh and Padgett, 2011) rather than accumulating the total cost of each activity involved in each designated repair method in light of local economic data (e.g. materials, equipment, and labor-force availability and cost). Using global repair cost ratios, which serve as a means of estimating repair cost as a fraction of replacement cost, may lead to over- or under-estimation of repair costs since these ratios fail to reflect variance in actual costs according to repair methods and local economic/environmental conditions. Some recent studies have addressed such pitfalls. For example, considering the expected CO2 emissions caused by various seismic retrofit and repair methods following seismic events, Wei et al.'s (Wei et al., 2015) risk-based CBA upheld the long-term environmental value of retrofit actions in a moderate seismicity area. These studies, however, still focus on only either economic or environmental impact, instead of simultaneously addressing all three aspects of sustainability. On the whole, although risk-based CBA has been identified as a practical tool for analyzing the tradeoff between the life-cycle benefits and costs of performance-based hazard designs, a holistic assessment that simultaneously address all three aspects of sustainability of a building exposed to natural-disaster risk has not hitherto been devised (Wei et al., 2015)5; (Hossain and Gencturk, 2014). Moreover, most related studies have ignored the effects of the selection of repair methods and local economic/environmental conditions when estimating the benefits and costs of designs.

2.4 Methodology

2.4.1 LCA Framework for Assessing the Sustainability Performance of Buildings Exposed to Natural Hazards

The purpose of the proposed LCA framework is to assess the life-cycle sustainability performance of buildings at risk from seismic events. This performance is evaluated and represented in terms of social, economic, and environmental metrics. As shown in Fig. 2.1, the LCA framework converts expected seismic building damage, arrived at using HAZUS seismic-loss estimation (Fig. 2.1(a)), into three types of quantifiable loss: number of fatalities, repair/replacement cost, and CO_2 emissions, which in turn serve as metrics for the objectives of the performance-based design (Fig. 2.1(c)). For those decision-makers who might wish to evaluate the desirability of a particular level of hazard-resistant design, a CBA can be conducted using any one, or any combination, of the three performance metrics (Fig. 2.1(c)).

Conventionally, the life-cycle of buildings (as shown in Fig. 2.1(b)) consists of three phases: construction, operation/maintenance, and end-of-life. Each phase has its own inherent impacts upon a building's sustainability performance. For example, the life-cycle environmental impacts from the construction phase can be presented as the energy consumed in all activities involved in building construction, including the manufacture and transportation of materials, and technical installations of components. The economic performance from the operation/maintenance phase can be estimated by evaluating the operation costs of water, lighting, maintenance of HVAC systems, and so forth. However, conventional LCA frameworks have become partially obsolete, insofar as they are unable to assess the sustainability performance of buildings in the face of natural disasters (Wei et al., 2015). Failing to incorporate such risks into LCA frameworks can lead to overestimates of buildings' long-term sustainability, since post-disaster recovery may result in major impacts. Therefore, to assess disaster-related impacts on buildings' sustainability performance, this dissertation has incorporated two new phases – hazard exposure and hazard mitigation – into a traditional LCA framework. The hazard-exposure phase can be utilized to predict the direct losses attributable to hazards, while the hazard-mitigation phase allows us to consider the upfront impacts of the mitigation design itself. In other words, the desirability of a particular hazard-mitigation design can be analyzed by comparing the benefits associated with the reduction in losses against the upfront cost of hazard-resistant design. In our proposed LCA framework, (Fig. 2.1(b)), the sustainable performance of a given phase is estimated by calculating and summing the corresponding impacts from each of its inherent activities. The advantage of this framework is its ability to capture the impacts of activities within the phase simply by calculating the two basic impact sources – material and equipment usage, which are often used as two major references in any economic- or environmental-impact estimation of the cost of construction work (Padgett and Tapia, 2013).

It should be noted that both the operation/maintenance and end-of-life phases (bold dotted boxes in Fig. 2.1(b)) have been excluded from the present study because their effects on sustainability performance are not directly influenced by structural vulnerability. In other words, it is only during the hazard-exposure and hazard-mitigation phases that the building's performance will be affected by hazard-resistant design (or the lack thereof). Finally, according to the International Organization for Standardization (ISO, 2006), a standard LCA should include four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. The goal of the present LCA is to assess buildings' lifetime sustainability performance resulting from natural disaster risks. In terms of its scope, the system boundary includes all activities contributing to the impact assessment within the entire life cycle of the building(s) in question. The functional units used here are the number of fatality per building for social metric, the amount of money per square meter of a building ($\$/m^2$) for economic metric, and the amount of CO_2 per square meter of a building (CO_2/m^2) for environmental metric. With regard to the inventory development of the LCA, the costs and environmental impacts of local materials and equipment are mainly drawn from the research of Huberman and Pearlmutter (Huberman and

Pearlmutter, 2008), which estimates the initial costs and embodied energy of a typical Israeli RC building in light of local material resources and production technologies. Cost- and environmental data that were *not* identified by Huberman and Pearlmutter have been drawn from a variety of sources (Popescu et al., 2003); (EPA, 2008); (TCR, 2008); (EIA, 2010); (EPA, 2014), since there is currently no single database that includes all the types of information discussed in this study.

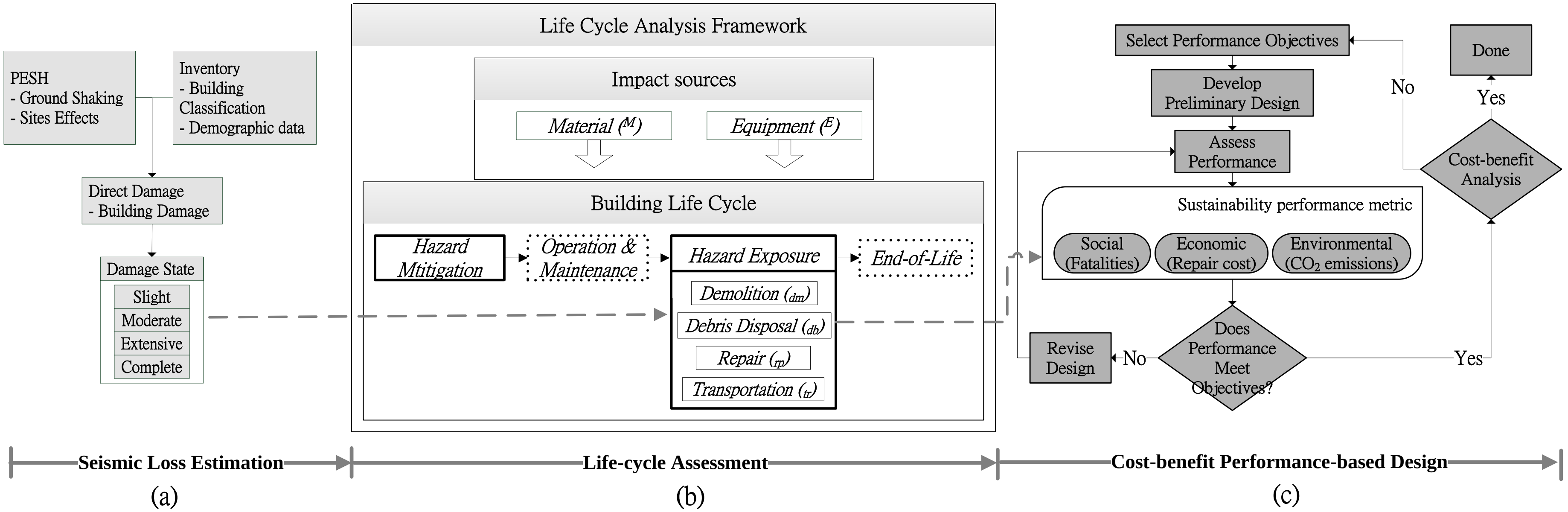

Fig. 2.1. Procedure for life-cycle cost-benefit assessment of a sustainability-performance-based seismic design: (a) HAZUS earthquake risk assessment (modified from(Kircher et al., 2006b); (b) LCA framework: bold solid = life cycle phases considered; bold dotted = life cycle phases not considered; (c) Performance-based seismic design (modified from FEMA (FEMA, 2006a).

2.4.2 Assessment of Building Seismic Damage and Repair Methods

The evaluation of building damage caused by earthquakes is crucial to the assessment of buildings' sustainability performance. Performance, in terms of repair cost as well as the amount of CO_2 emissions, depends mainly on the chosen repair methods, which in turn depend mainly on the extent to which the building has been damaged. In this study, this dissertation uses the HAZUS seismic-loss estimation method (described in the first sub-section below) to predict building damage. A range of retrofit and repair measures corresponding to the HAZUS seismic-damage states of RC buildings is then introduced in the second sub-section.

HAZUS Seismic-Loss Estimation

Seismic-related losses have been conceptualized primarily as a function of damage to buildings (Kircher et al., 2006b). Most social-loss models, for example, are based on the assumption that the number and severity of casualties are strongly correlated to the degree of building damage (Spence et al., 2003); (Jaiswal and Wald, 2010). Economic-loss research is likewise dominated by the notion that damage to nonstructural systems and contents is caused by damage to buildings (Kircher et al. 2006). HAZUS, a standardized risk-assessment software developed by the U.S. Federal Emergency Management Agency (FEMA), is used for estimating building seismic damage in this study. As shown in Fig. 2.1(a), its Potential Earth Science Hazards (PESH) module makes an initial determination of the characteristics of potential seismic events – such as their locations, magnitudes and frequencies – that would affect the system of interest. The Inventory module collects data on geological characteristics for determining site effects such as soil attenuation equations, which characterize the rate at which the amplitude of the seismic waves decreases as the waves propagate outward from the epicenter (Grossi et al., 2005). Additionally, data about the built environment is collected, including building structural types, design codes and so forth. In the Direct Damage module, damage is estimated in terms of probabilities that certain states of damage will be exceeded at a given level of ground shaking. These damage probabilities are then converted into fractions of specific building populations that would be in particular damage states in the wake of a seismic event. Unlike most earthquake-loss-estimation software programs, which are tailored to a specific country and may or may not be suitable for use in international settings, HAZUS has been widely validated for its applicability both inside and outside its country of origin, the United States (Kircher et al., 2006a); (Gulati, 2006, Levi et al., 2010); (Ploeger et al., 2010); (Peterson and Small, 2012). Moreover, HAZUS allows replacement of its databases as well as modifications to its default functions using local parameters, making it highly suitable for our case study of expected building damage in Tiberias, Israel.

Seismic Retrofit and Repair Measures

Pre-event retrofit and post-event repair measures are determined mainly by the type of structure, its failure mechanisms, and its level of damage. An RC-frames structure, defined as building type C1 in the FEMA report “Techniques for the Seismic Rehabilitation of Existing Buildings” (FEMA, 2006b), was adopted as the case building in this study. This structure type usually consists of cast-in-place concrete moment frames, which develop stiffness through column-beam systems to resist lateral forces. However, many RC structures built to old seismic codes have innately low resistance to lateral loads during earthquakes because they lack significant structural supporting components such as shear- or load-bearing walls; this can result in significant inelastic deformations (FEMA, 2006b)b; (Zou et al., 2007). Consequently, due to the weak column/strong beam effect, the typical seismic responses of these older buildings include failures of brittle soft-story and/or column lateral collapse (FEMA, 2006b). The present study adopted the concrete-jacketing method developed by Shohet et al. (Shohet et al., 2015), in which all columns of an old concrete frame are jacketed with RC to achieve a ratio of column-to-beam strength equivalent to the requirements of Israeli regulation SI 413 (SI, 1995).

The cardinal purpose of post-seismic repair is to restore the seismic performance of damaged buildings to their pre-event levels. In practice, various repair measures may exist that correspond to a level of severity of the damage; and the choice of one of these alternatives over another may involve factors such as time constraints, availability of techniques and resources, and so forth. The remainder of this section describes the four seismic damage states of a RC building as set forth in the HAZUS technical manual (FEMA, 2013), and the corresponding repair measures utilized in the present study. It should be noted that although the repair measures proposed here have been chosen based on local experts' analyses, other alternatives can always be considered to fit special needs.

As defined in HAZUS, a state of *slight damage* consists of flexural- or shear-type hairline cracks found in the concrete surfaces of columns. Since these minor cracks rarely affect structural stability, the two main objectives of restoration are to seal them against the flow of water, and to improve the structure's appearance; thus, bonding these cracks with epoxy resin is a common repair option (Sudhakumar, 2001). In a state of *moderate damage*, most columns experience larger shear cracks and spalling, so one practical repair method is the application of shotcrete patches (Årskog et al., 2004). In a state of *extensive damage*, buckling failures or shear failures often result in partial collapses, and RC jacketing can be used to repair those columns that are substantially damaged (Julio et al., 2003). A complete process of RC jacketing for damaged columns should include the following actions: removing damaged concrete, preparing the interface surface, applying the bonding agents, placing the reinforcement, and covering with new concrete (Hossain and Gencturk, 2014). The present study has assumed conservatively that all columns are repaired with the aforementioned methods in correspondence with particular damage states.

Finally, in the *complete damage* state, structures are collapsed or nearly collapsed as a result of significant inelastic deformations of non-ductile elements, i.e. failures of the brittle soft-story, or horizontal crash of columns. In such cases, repair is not considered technically practicable, because aftershocks may cause uncontrolled collapses that pose a serious threat to workers. In contrast to the partial demolition of buildings in other, less severe states of damage, the wholesale demolition of completely damaged buildings involves more complex techniques and heavier equipment, and as such should be given special consideration when it comes to economic and environmental impacts. For example, compared with lesser damage levels – which generally require that only the above-ground structure be (partially) demolished – complete damage requires demolition of both above-ground structures and below-ground foundations, and therefore significantly more work (Richard and Mark 2010). This study adopts Richard and Mark's estimates of the quantities and costs of equipment and labor for the activities associated with demolishing a three-story RC building: these involve crushing concrete using crawler cranes equipped with wrecking balls, and chopping with hydraulic excavators. Table 2.2, adapted from (Wei et al., 2015), summarizes all the relevant repair/replacement measures, along with information on how these correspond to different states of damage.

Table 2.2. Building damage states and corresponding repair measures

Damage state	Repair measure	CO_2 emission (kg/m^2)	Activities and data source
Slight	Epoxy resin	4.1	Injecting epoxy resin (Althaus et al., 2007)
Moderate	Shotcrete patching	27.7	Patching shotcrete (Å rskog et al., 2004)
Extensive	Reinforced concrete jacketing	170.4	Hydrojetting (Å rskog et al., 2004); applying bonding agent (Althaus et al., 2007); and jacketing with reinforced concrete (Masanet, 2012)
Complete	Replacement	446.7	Demolition (Richard and Mark 2010); and reconstruction (Huberman and Pearlmutter, 2008)

2.4.3 Performance-based Seismic Design and Sustainability Metrics

As shown in Fig. 2.1(c), performance-based design is an iterative process that begins with selecting performance objectives, followed by an assessment of whether or not the preliminary design satisfies those objectives; if it does not, redesign is undertaken until the desired level of performance is achieved (FEMA, 2006a). Performance objectives are defined as the acceptable level of consequential losses that would occur as a result of seismic building damage. Losses can be expressed in various forms depending on the purpose(s) of the designed facilities. In the case of hospitals, for example, the downtime resulting from building damage is of paramount concern, among other losses including the usual performance metrics for a residential-building design: number of fatalities, repair cost, and repair energy consumption

Among all types of natural disaster, earthquakes tend to cause the most physical damage to buildings and thus lead to the most significant social, economic and environmental impacts (Ayyub, 2014). In the HAZUS seismic-loss assessment methodology, building damage includes both structural and non-structural damage. Structural components include load-carrying structures such as columns and beams; nonstructural components consist of anything not responsible for load-carrying, such as architectural elements and HVAC instruments. For purposes of loss estimation, this study considers only structural damage, which plays by far the most crucial in seismic-related losses (Kircher et al., 2006b). Also, loss estimations generally divide losses into “direct” and “indirect” categories (Kircher et al., 2006b). Direct losses are defined as those caused directly by building damage, such as repair/replacement costs, number of casualties, and number of displaced households. On the other hand, indirect loss assessment includes the broad and long-term implications of direct impacts: for example, changes in the area’s employment profile (FEMA, 2013). Although indirect losses often play a crucial role in post-event recovery planning, they have been excluded from this study due to the difficulties of collecting post-event loss data and of quantifying its effects, which may take years to appear and even longer to be properly understood (Bird and Bommer, 2004). Therefore, based on the direct losses resulting from structural damage to RC buildings, the following sections propose three performance metrics – social, economic, and environmental – and the methods for estimating them.

Social Metrics

Though direct social losses may include such factors as displaced households and short-term shelter needs, the ability to prevent deaths during earthquakes has naturally been seen as the most important performance aspect of a seismic building design. Theoretically, the number of casualties due to building damage during earthquakes can be estimated based on the assumption that there is a direct relationship between building damage states and numbers of casualties – this relationship is often referred to as the *casualty rate* (Spence and So, 2011). However, analytical models for estimating casualty rates have yet to be fully developed because of our relatively poor understanding of the relationship between casualties and building damage (Spence and So, 2011). Instead, empirical approaches using historical casualty data and experts' analyses have been seen as a practical alternative. For instance, the casualty rates used in HAZUS were calibrated from the estimation presented by the U.S. Applied Technology Council (ATC) (ATC, 1985), which in turn were based on experts' analyses and historical casualty data derived from several earthquakes in California (FEMA, 2013). Most other seismic casualty loss-estimation methods have used a similar combination of expert opinion and historical data; one example being KOERI, which is based on empirical data from Turkish earthquakes (Erdik et al., 2011). In some earthquake-prone regions, casualty rates can be estimated based on historical data alone, due to its relative abundance. Spence et al. (Spence and So, 2009), for example, developed a prototype global casualty rate for estimating losses in countries with high seismicity such as Taiwan and Iran. However, for areas of moderate seismicity, expert analysis continues to play an important role due to the lack of past casualties data.

The present study utilizes the methodology developed by Shapira et al. (Shapira et al., 2014) for evaluating casualty rates in areas that have little or no historical data, such as the city of Tiberias, where the last lethal earthquake occurred in 1927. Based on a Modified Delphi Technique reaching a consensus higher than 70%, this methodology surveyed a group of Israeli experts from diverse disciplines, including structural engineers, physicians, risk-management professionals and search-and-rescue team members, all of whom had experience dealing with earthquakes. Once we take into account the factors that tend to affect local casualty rates – the lower standard of building finishing materials, and the residents' lack of experience and knowledge of earthquakes – the resulting local casualty rates, as shown in Table 2.3, are higher than those used in HAZUS.

Once the casualty rates are determined, the expected number of fatalities associated with different building damage states can be obtained by multiplying the casualty rate of a building by its number of occupants at the time of an event. As such, the number of fatalities is also affected by the occupancy of buildings at the time of the events. The present study assumes that all residents are at home between the hours of 12:00 AM and 6:00 AM (nighttime); whereas during the daytime, the residential population is defined only as those who do not need to go to school or work, according to local census data. Here, this dissertation has assumed a worst-case scenario from the point of view of occupancy exposure, i.e. that all seismic events occur during the night, although a confidence interval for the resulting fatalities can be defined by taking into account all scenarios of occupancy exposure at the time of the events.

Table 2.3. Casualty rates for RC structures (% of occupancy)

Injury severity	Damage state			
	Slight	Moderate	Extensive	Complete
Light	0.05	0.25	7.5	40
Moderate	0	0.03	0.15	20
Severe	0	0	0.00125	5
Fatal	0	0	0.0012	10

Economic Metrics

Direct economic losses due to earthquakes are generally conceived of as either the costs of repairing and replacing damaged structures, or the losses attributable to the inability of damaged buildings to function properly, including rental-income loss and relocation expenses (Bird and Bommer, 2004). The present study considers only the economic losses from repair/replacement, as the second type of economic loss is extremely variable and complex, to the point that modeling it might seem almost purely speculative.

Repair costs associated with a particular damage state are often represented as a fraction of the full replacement cost of the building. For example, HAZUS defines the repair costs for slight, moderate, extensive, and complete structural damage to a single family dwelling to be 0.5%, 2.3%, 11.7%, and 23.4% of its replacement cost, respectively. These fractions, also called *repair cost ratios*, are the same values that were presented by the ATC (ATC, 1985), which were derived from historical earthquake-loss data from California (FEMA, 2013). Various other repair cost ratios for different types of structures have been created based on local historical loss data in other regions (Bird and Bommer, 2004); Padgett et al. 2010; (Zhang et al., 2011); (Valcárcel et al., 2013). However, as with casualty rates in low-seismicity areas (see above), realistic repair cost ratios are extremely difficult to estimate in places where historical loss data is rare or nonexistent. As such, this dissertation proposes a method that directly calculates the costs arising from repair measures corresponding to particular damage states, taking into consideration local economic data on materials, equipment, the labor force, and so forth. As previously mentioned and shown in Fig. 2.1(b), the economic costs within a life-cycle phase for a given damage state (EC_i) can be estimated by calculating and summing the material and equipment usage corresponding to each of the activities j that are inherent to a specific damage state i, as shown in Eq. (2.1).

$$EC_i = \sum_j \left(EC_{i,j}^M + EC_{i,j}^E\right) \tag{2.1}$$

$i = s(slight), m(moderate), e(extensive), c(complete)$ &

$j = dm(demolition), db(debris\ disposal), rp(repair), tr\,(transportation)$

The economic losses attributable to material usage involved in an activity j for a specific damage state i ($EC_{i,j}^M$) can be calculated using Eq. (2.2).

$$EC_{i,j}^M = \sum_m Q_m \cdot C_m^{EC} \tag{2.2}$$

where Q_m is the quantity of material m attributable to the activity j for a specific damage state i, C_m^{EC} is the unit cost of material m.

The economic losses attributable to equipment usage involved in an activity j for a specific damage state i ($EC_{i,j}^{E}$) can be calculated by Eq. (2.3).

$$EC_{i,j}^{E} = \sum_{e} T_{e}^{j} \cdot F_{e}^{EC} \tag{2.3}$$

where F_{e}^{EC} is the cost factor per unit of time for equipment *e*, including the cost of the equipment, fuel, and labor, which can be found in most construction-cost estimating references (Popescu et al., 2003). T_{e}^{j} is the net operation time for equipment e, and the choice of formula for the calculation of T_{e}^{j} depends on the activity j. For demolition or repair activity, T_{e}^{j} is simply the net operation time for equipment e. However, the T_{e}^{j} for debris disposal or transportation activity is calculated using Eq. (2.4):

$$T_{e}^{j} = \sum_{n} \frac{Q_{ne}}{CP_{e}} \cdot \frac{D_{ne}}{S_{e}} \text{ for } j = db, tr \tag{2.4}$$

where Q_{ne} is the quantity of debris ($j = db$) or construction material ($j = tr$) type n transported between sites by transportation equipment *e*; D_{ne} is the distance that debris or material type n travels using transportation method *e*; CP_{e} is the capacity of transportation equipment *m*; and S_{e} is the average travel speed of transportation equipment *e*.

Environmental Metrics

CO_2 emissions are chosen as our environmental metric because they have been widely used as such for evaluating and reporting the environmental impacts of products and processes. For example, recently introduced U.S. Environmental Protection Agency (EPA) rules are designed to combat global warming by reducing the amount of CO_2 emissions from the electric-power sector to 30% below their 2005 level by 2030 (Gillenwater, 2014). In the area of seismic design specifically, CO_2 emissions arising from post-hazard recovery have recently been proposed as both performance metrics (FEMA, 2006b)a; (Hamburger et al., 2012) and sustainability rating systems (Comber and Poland, 2013). For instance, one of the stated aims of ATC's latest seismic design guide – *Next-Generation Building Seismic Performance Assessment Methodology* (FEMA, 2012) – is to address, in addition to social and economic impacts, the environmental consequences associated with building damage, including GHG emissions and energy utilization. Unlike the previously mentioned usual methods for evaluating repair-cost, the CO_2 emissions associated with repair/reconstruction to different building damage states are not available in historical loss data as a result that they have almost never been calculated or recorded during post-event recovery. As such, this dissertation proposes a method that directly calculates the CO_2 emissions arising from repair measures corresponding to particular damage states, taking into consideration local CO_2 coefficient on materials, equipment, and so forth. For purposes of the present study, this dissertation has defined a *CO_2 emission ratio* as the ratio of emissions from repair activities to those from new construction of the building. The environmental loss within a life-cycle phase for a given damage state (EN_i) is estimated by calculating and summing the material and equipment usage corresponding to each of the activities j inherent to a specific damage state i.

$$EN_i = \sum_j \left(EN_{i,j}^M + EN_{i,j}^E\right) \qquad (2.5)$$

$i = s(slight), m(moderate), e(extensive), c(complete)$ &

$j = dm(demolition), db(debris\ disposal), rp(repair), tr(transportation)$

The environmental losses attributable to material usage involved in an activity j for a specific damage state i ($EN_{i,j}^M$) can be calculated using Eq. (2.6):

$$EN_{i,j}^M = \sum_m Q_m \cdot C_m^M \qquad (2.6)$$

where Q_m is the quantity of material m attributable to the activity j for a specific damage state i, and C_m^M is the CO_2 coefficient of material m.

The environmental losses attributable to equipment usage involved in an activity j for a specific damage state i ($EN_{i,j}^E$) can be calculated using Eq. (2.7):

$$EN_{i,j}^E = \sum_e T_e^j \cdot F_e^{EN} \qquad (2.7)$$

where F_e^{EN} is the emission factor per unit of time for equipment e; this can be obtained by Eq. (2.8):

$$F_e^{EN} = FU_{l_e} \cdot C_l^F \qquad (2.8)$$

where FU_{l_e} is the amount of fuel type l required by equipment e per unit of time; and C_l^F is the CO_2 coefficient of fuel type l. T_e^j is the net operation time for equipment e, and the formula for the calculation of T_e^j depends on the specific activity j. For demolition and repair, T_e is simply the net operation time for equipment e, while the T_e for debris disposal and transportation can be obtained using Eq. (2.4).

2.4.4 Risk-based Life-cycle CBA

CBA can serve as a straightforward tool for analyzing tradeoffs between benefits and upfront costs in hazard mitigation design. As previously mentioned, instead of scenario-based, a risk-based CBA is a more useful basis for projections of buildings' long-term performance in areas of moderate-frequency seismicity (but high vulnerability). To take into account the uncertainty associated with seismic events, the Probabilistic Seismic Hazard Analysis (PSHA) method (McGuire, 2001) have been used to investigate the likelihood of magnitudes and frequencies of seismic events affecting the areas of interest. Coupled with the life-cycle benefits and the costs associated with hazard-resistant design derived from our proposed LCA framework, a risk-based life-cycle CBA can be used to assess the long-term sustainable value of the design. Each earthquake event i has an annual probability of exceedance (p_i), and the associated losses (L_i) to an inventory can be obtained using Eq. (2.1) for economic loss, and Eq. (2.5) for environmental loss, while the social loss is obtained by multiplying the rates of fatal injury (Table 2.3) by the designated occupancy of the building. As a result, the *expected annual loss* ($E(L_i)$) for a given event can be determined using Eq. (2.9), and the *average annual loss* (AAL) can then be obtained by summing all expected annual losses, as shown in Eq. (2.10). Additionally, an exceedance probability (EP) curve can be depicted by $\mathrm{p_i}$ as y-axis and L_i as x-axis, with the area below the curve representing AAL. In other words, for a given building inventory facing seismic risk, an EP curve is a probabilistic representation of a certain level of loss that will be exceeded in a given annual probability of exceedance (Grossi et al., 2005). In the following section, three EP curves will be used to depict the discrepancy between the losses suffered by as-built and retrofitted inventories with different levels of design.

$$E(L_i) = p_i \cdot L_i \tag{2.9}$$

$$AAL = \sum E(L_i) = \sum p_i \cdot L_i \tag{2.10}$$

where p_i is the annual probability of exceedance of earthquake event i and L_i is the associated losses with earthquake event i to an inventory.

The benefit of a retrofit design (B_r) can be obtained by first calculating the difference in AAL between as-built and retrofitted inventories, and then calculating the difference using a discount rate r and a service lifetime T, as shown in Eq. (2.11). Finally, the benefit-cost ratio for the retrofit design (BCR_r) can be arrived at by dividing the total expected benefit by the upfront cost of retrofit (C_r), $BCR_r = B_r/C_r$. The investigated retrofit design can be described as cost-effective if the BCR_r is greater than one. However, it should be noted that in a performance-based design, a BCR_r less than one may still be worthwhile, if its expected performance satisfies the design objectives. In certain cases, for instance, performance objectives regarding the avoidance of loss of life are paramount, regardless of the economic feasibility of the design. Even in such situations, however, risk-based CBA can serve as a useful tool with which to investigate optimum levels of performance for the achievement of a cost-efficient investment (Fig. 2.1(c)).

$$B_r = \sum_{t=1}^{T} \frac{AAL_{as-built} - AAL_{retrofitted}}{(1+r)^t} \tag{2.11}$$

2.5 Case Study

Two case studies were conducted to illustrate the proposed methodology. The first illustrates its application to the evaluation of the three sustainability metrics – number of fatalities, repair cost, and repair-related CO_2 emissions – at the four possible seismic-damage states of an individual RC building. In the second case study, HAZUS seismic-loss estimation was first employed to obtain the expected number of buildings, within the inventory of old (pre-1980) RC buildings in the city of Tiberias, that would be in each of these four damage states following each of 12 hypothetical seismic events. Finally, based on the sustainability metrics of a single building derived from the first case study, risk-based life-cycle CBAs were conducted to test the social, economic and environmental desirability of implementing two different retrofit designs within the same building inventory used in the second case study.

2.5.1 Sustainability Metrics for Performance-based Seismic Retrofit Design of a RC Building

Our three sustainability metrics were evaluated for a typical three-story, two-bay old RC residential building with a total floor area of 600 m^2 in the city of Tiberias. This dissertation choses this building type for our first case study because, having been built before 1980 when the first Israeli national seismic building code was enacted, it embodies a high level of seismic risk. In our previous study (Wei et al., 2014), where the fragility curve for such pre-1980 RC buildings was estimated by experts as “Pre-Code” in HAZUS seismic design settings (Levi et al., 2010), this seismically vulnerable building inventory contained a total of 2,014 buildings; these represented 45% of the total buildings in the city, but were predicted to cause 62% of total average annual human losses from earthquakes. Rather than the fragility curve estimated by the means of expert judgment, this study uses the fragility curves obtained by Shohet et al. (Shohet et al., 2015), where pushover analysis method was employed for investigating the seismic response of both before retrofitting and after two different schemes of retrofitting that consist of concrete jacketing designs that were selected to achieve compliance with SI 413, Design Provisions for Earthquake Resistance of Structures (SI, 1995). Retrofitting the original design RC_o, these two designs were intended to satisfy two contrasting objectives, seismic performance versus construction cost: with RC_{r2} designed to achieve HAZUS high-code performance at a higher retrofit cost, and RC_{r1} to achieve HAZUS mid-code performance at a lower retrofit cost (Table 2.4).

Table 2.4. Retrofit designs (adapted from (Shohet et al., 2015)

Design	Column depth & width (mm)	Reinforcement ratio of column	Maximum interstory drift	HAZUS fragility curves
RC_o	400×400	0.005	0.187	Pre-code
RC_{r1}	550×550	0.0075	0.129	Mid-code
RC_{r2}	700×700	0.01	0.096	High-code

Conducting a Modified Delphi panel with 26 local experts, we arrived at casualty rates, with four levels of injury severity corresponding to four structural-damage sates, as shown in Table 2.3. Among all four investigated levels of injury, only the rates of fatal injury (the last row of Table 2.3) have been used as the social metric in this study, for reasons discussed above. Using the latest Israeli census, conducted in 2008 by the National Bureau of Statistics, we estimated the average full occupancy of a case building to be 24 people (Shohet et al., 2015). Assuming that all occupants are at home when the event occurs (the worst-case scenario), the expected numbers of fatalities at different levels of building damage are shown in Table 2.5. The results reflect that deaths in earthquakes are caused chiefly by building collapses, while buildings that do not collapse have very little influence on the death toll (0.0003 deaths per building in a state of extensive damage).

In terms of our economic metric, the repair/replacement costs attributable to the hazard exposure phase (Fig. 2.1(b)) were estimated based on the assumption that all damaged buildings will be restored, through designated methods (Table 2.2), to a state of compliance with the modern Israeli building code. Table 2.6 presents the hazard-exposure-related repair costs resulting from Eq. (2.1). In Table 2.6, the cost ratio of each damage state represents the normalized value of the initial construction cost of a new building, which is $1,280 per square meter according to the 2014 Price Indices of Residential Buildings from the Central Bureau of Statistics (CBS, 2015). The calculation for hazard-exposure-related CO_2 emissions, serving as our environmental metric, is similar to the calculation of repair cost, in that both assume that a damaged building will be restored to a condition complying with the modern building code. Table 2.7 presents the CO_2 emissions arising from repair activities from Eq. (2.5) and the decomposition of emissions from the use of materials (Eq. (2.6)) and from the use of equipment (Eq. (2.7)) in each damage state are shown in

Table 2.8. In Table 2.7, the CO_2 emission ratio of each damage state represents the normalized value of the emission from initial construction of a new building, which is 379kg-CO_2 per square meter according to the study of (Wei et al., 2015), where a modern local RC building was estimated for its emission from construction. It should be noted that the ratios shown in Table 2.6 and 2.7 can be served as references for the evaluation of economic and environmental impacts of similar RC buildings due to seismic hazard. Finally, the upfront economic and environmental impacts of the two aforementioned retrofit designs (i.e. the hazard-mitigation phase in Fig. 2.1(b)) were also calculated using Eq. (2.1) and Eq. (2.5), respectively (Table 2.9).

To predict the amount and type of debris that will be generated as a result of shaking damage Q_{ns} of Eq. (2.4), following the HAZUS seismic debris-estimation methodology, this dissertation has calculated two classes of debris generated from both non-structural and structural components, corresponding to different damage states: reinforced concrete and steel members (Type 1), and brick, wood and other waste (Type 2). The amount of debris has been estimated based on the damage state of a specific building type. For example, the amounts (by weight) of Type 1 debris derived from a RC building of type C1 subjected to slight, moderate, extensive and complete damage are estimated to be 0%, 5%, 33%, and 100%, respectively (FEMA, 2013). In addition, it is worth noting that the building inventory data is collected based on census tract areas in HAZUS and the entire composition of the buildings within a given census tract is assumed to be lumped at the centroid of the census tract. Consequently, the damage of buildings will be computed at the centroid of the census tract (FEMA 2013). Based on the aforementioned assumption, this dissertation has also assumed that the travel distances of debris disposal and material transportation D_{ne} of Eq. (2.4) are the shortest routes from the centroid of the census tract to the designated landfill and factories. In the study, one landfill and two factories, including one for ready mix concrete and one for reinforcement bars, located in the suburban areas of the city are used for the calculation of travel distances. It should be noted that one can always tailor the locations and number of landfill and factories to evaluate travel distances depending on local conditions.

These results indicate that the values of all three metrics depend chiefly on the extent of building damage, ranging from 0 to 2.4 in the number of fatalities (Table 2.5); from 0.012 to 1.12 in the cost ratios (Table 2.6); and from 0.01 to 1.18 in the CO_2 emissions ratios (Table 2.7). Since the three impacts all exhibit steep increases in cases where the building is completely damaged, the prevention of a building entering a state of complete damage can be tentatively identified as an effective strategy for mitigating all three impacts in the face of seismic hazards. It should also be noted that, since they depend chiefly on the repair methods chosen, the estimated values of the economic and environmental metrics can vary widely alongside different repair designs and local economic conditions (e.g. prices for raw materials, equipment, and labor). However, this section has demonstrated how sustainability metrics for a performance-based seismic design can be achieved through LCA. One can always tailor the proposed methodology to evaluate other specific requirements of performance-based design, while taking into consideration various designated repair and retrofit designs as well as economic data.

Table 2.5. Social metric – number of fatalities

Damage	Fatality ratio[a]	Number of fatalities[b]
Slight	0	0
Moderate	0	0
Extensive	0.000012	0.0003
Complete	0.1	2.4

[a] Fatality ratios are calculated by dividing the expected number of fatalities by full building occupancy

[b] Assumes full building occupancy is 24 people and that they are all at their building during the event

Table 2.6. Economic metric – repair costs

Damage	Repair Cost ($\$/m^2$)	Cost ratio[a]
Slight	15	0.012
Moderate	83	0.065
Extensive	228	0.18
Complete	1,434	1.12

[a] Calculated by dividing repair cost by the initial construction cost of $1,280/m^2

Table 2.7. Environmental metric – CO_2 emissions

Damage	CO_2 emission (kg/m^2)	CO_2 emission ratio[a]
Slight	4	0.01
Moderate	27	0.07
Extensive	171	0.45
Complete	447	1.18

[a] Calculated by dividing the emissions from repair by the emissions from the initial construction of 379kg-CO_2/m^2

Table 2.8. CO_2 emissions from the use of equipment and materials

Damage	$EN_{i,j}^E$		$EN_{i,j}^M$			
	Activity	CO_2 (kg/m^2)	Material	C_m^M (kg/m^3)	Q_m (m^3)	CO_2 (kg/m^2)
Slight	Injecting epoxy resin	3.6				
Moderate	Application of shotcrete	14	Concrete	427.2[a]	6.9[b]	4.9[c]
Extensive	Hydro jetting	84				
	Cleaning of reinforcement	22				
	Jacketing with reinforced concrete	40	Steel Concrete	8,635[d] 427.2	0.04[e] 6.9	0.59[f] 4.9
Complete	Demolition	42				
	New construction	379				

[a] Calculated by multiplying the coefficient of ready mix concrete 0.178 kg-CO_2/kg (EPA 2004) by density of concrete 2,400 kg/m^3

[b] Volume of all columns of a building

[c,f] Calculated by dividing the emission of materials ($C_m^M \times Q_m$) by the total floor area of a building

[d] Calculated by multiplying the coefficient of reinforcement bar 1.1 kg-CO_2/kg (EPA 2004) by density of reinforcement bar 7,850 kg/m^3

[b] Volume of the reinforcement bars of all columns of a building

Table 2.9. Economic and environmental cost of retrofit designs

Design	Cost (\$/m^2)	Cost ratio[a]	CO_2 emissions (kg)	CO_2 emissions ratio[b]
RC_{r1}	100	0.08	300	0.13
RC_{r2}	212	0.17	485	0.21

[a] Calculated by dividing repair cost by the initial construction cost of \$1,280/m^2

[b] Calculated by dividing the emissions from retrofit by the emissions from the initial construction of 379kg-CO_2/m^2

2.5.2 Risk-based CBA for Seismic Retrofitting of Buildings at the Regional Level

This dissertation used a risk-based CBA to investigate the cost efficiency, in terms of the three sustainability performance factors, of retrofitting a portfolio consisting of 2,014 old RC buildings in Tiberias. Three sub-cases of the building inventory – as-built (RC_o) and two different levels of retrofit design (RC_{r1} and RC_{r2}) (Table 2.3) – were evaluated for their sustainability metrics vis-à-vis potential seismic events. First, this dissertation used HAZUS software to estimate the building damage that would follow the 12 synthetic earthquakes that were determined using a PSHA by Shohet et al. (Shohet et al., 2015). The average annual loss in the number of damaged buildings (AAL_D) in each earthquake scenario could be found using Eq. (2.10). As shown in Fig. 2.2, we found that the portion of AAL_D that consisted of slightly damaged buildings was slightly higher among RC_{r1} and RC_{r2} inventories, at 10.2 and 10.9 respectively, than among the as-built inventory (9.2). However, the AAL_Ds comprising moderate, extensive and complete damage each decreased to some degree in the two retrofitted inventories, as compared to the as-built inventory. The AAL_D in completely damaged buildings, for example, was reduced from 2.4 buildings of the as-built inventory to 0.8 and 0.4 buildings of the RC_{r1} and RC_{r2} inventories, respectively.

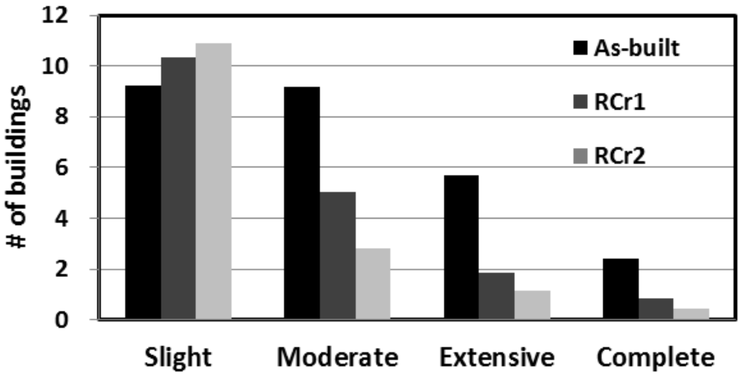

Fig. 2.2. Average annual losses by building-damage states

In terms of social metrics, the expected numbers of fatalities in each earthquake scenario were obtained by multiplying the number of buildings in each state of damage by that state's corresponding number of fatalities, as presented in Table 2.5; the average annual loss in the number of fatalities (AAL_S) could then be arrived at using Eq. (2.10). The results show that a very small value of the AAL_S is attributable to extensively-damaged buildings in the as-built category (only 0.002 people, a value too small to be shown in Fig. 2.3). However, all "non-fractional" deaths, and therefore all deaths, are caused by completely-damaged buildings; and the AAL_S for this damage state range from 5.8 fatalities in the as-built inventory to 1.9 and 1 in the RC_{r1} and RC_{r2} inventories, respectively (Fig. 2.3).

Using Eq. (2.10), we obtained the average annual loss in terms of repair cost (AAL_{EC}). As shown in Fig. 2.4, the AAL_{EC} is lower by 61% in the RC_{r1} inventory, and by 77% in the RC_{r2} inventory, as compared to the as-built inventory. It can also be observed that the reduction in AAL_{EC} associated with completely-damaged buildings contributes the lion's share of the total reduction. For instance, comparing the as-built and RC_{r2} inventories, RC_{r2}'s lessened losses that are attributable to completely-damaged buildings (\$1,700,804) represent 65% of the total difference of \$2,632,089. Moreover, from the right tails of the EP curves of repair costs (Fig. 2.5), we can see that the repair-cost reductions achieved by retrofitted buildings become more significant as seismic magnitudes become more severe (lower exceedance probability). For example, retrofitting with the RC_{r2} design was found to reduce the probable maximum loss (PML) by \$792,923,603 where the exceedance probability was 0.07%, but by only \$1,385,533 where the exceedance probability was 1%. Similarly, the developing trend of total losses being mainly controlled by changes in the number of completely-damaged buildings can also be observed in average annual losses measured by CO_2 emissions (AAL_{EN}) (Fig. 2.6). In sum, these results indicate that a completely-damaged building will cause disproportionately large amounts of loss, and preventing buildings from entering this state can therefore be confirmed as an efficient approach for reducing the overall impacts of seismic events. Although damage cannot be entirely avoided through the application of the proposed retrofit designs, parts of the retrofitted buildings that would otherwise have been expected to become completely damaged are now subject to less severe damage levels.

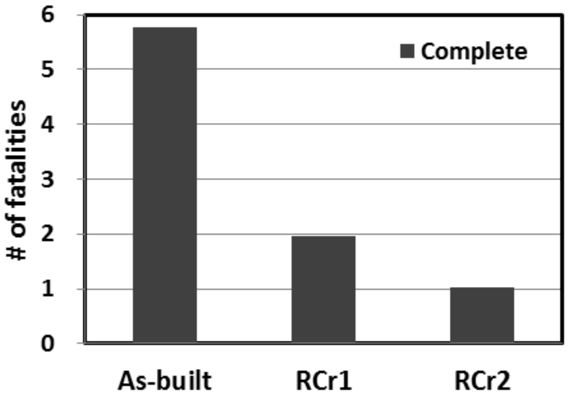

Fig. 2.3. Average annual losses by number of fatalities (social metric)

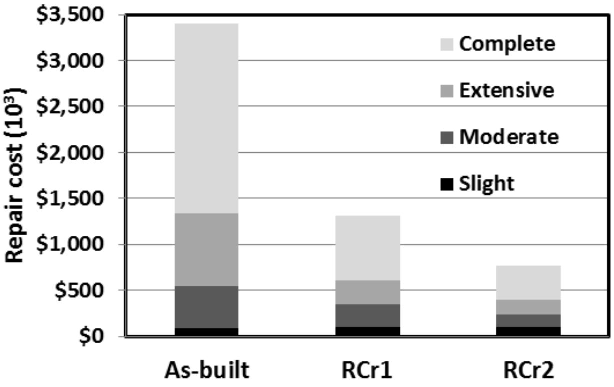

Fig. 2.4. Average annual losses by repair costs (economic metric) attributed to damaged buildings

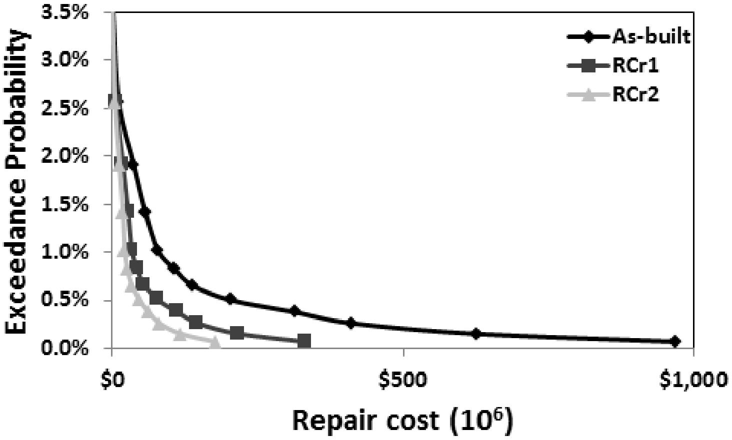

Fig. 2.5. Exceedance probability curves of repair costs

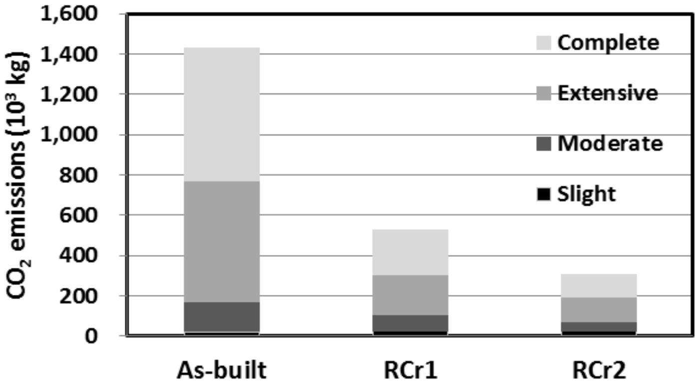

Fig. 2.6. Average annual losses by CO_2 emissions (environmental metric)

The construction costs of retrofitting all of Tiberias' 2,014 old RC buildings, calculated using Eq. (2.1), are \$102,072,960 and \$211,878,720 for the RC_{r1} and RC_{r2} designs, respectively (assuming that the cost of a particular retrofit type would be the same for each individual building). To discount the recurring annual benefits to a present value, a 20-year planning horizon was used, based on the assumption that the remaining life of these old buildings is 20 years. Meanwhile, a 3% discount rate was adopted, as has been suggested for CBA analyses of seismic rehabilitation of U.S. federal buildings (FEMA, 1994). Over a 20-year time period with a 3% discount rate, the repair-cost benefits of the RC_{r1} and RC_{r2} designs, in present values (B_r), were calculated using Eq. (2.11); this indicated that the $BCR_{r,EC}$ of the RC_{r1} and RC_{r2} designs were nearly 0.30 and 0.18, respectively (Table 2.10).

Unlike in economic analysis, discount rates are not recommended for environmental and social impacts in a CBA due to the inconsistent nature of nonmonetary values (Ciroth et al., 2008); (Padgett and Tapia, 2013). Therefore, the future expected benefits in regard to number of fatalities and CO_2 emissions are not discounted in this study. Using Eq. (2.11) with no discount rate, the CO_2-emissions benefits (B_r) of the RC_{r1} and RC_{r2} designs were calculated and are shown in Table 2.10. Comparing the up-front emissions from retrofit construction using Eq. (2.5), the $BCR_{r,EN}$ of the RC_{r1} and RC_{r2} designs were found to be nearly 0.51 and 0.37, respectively (Table 2.10). In terms of reduced fatalities, using Eq. (2.11) without a discount rate, the benefits (B_r) of the RC_{r1} and RC_{r2} designs were estimated as 76.3 and 94.9 lives saved, respectively. To translate fatalities into dollars, this dissertation adopted the statistical value of human life of \$1 million per person that was estimated by Shohet et al. (Shohet et al., 2015), based on the court-awards approach described in FEMA-227 (FEMA, 1992) modified using local data. Comparing the monetary benefit from reduced fatalities against the upfront retrofit costs, the $BCR_{r,S}$ of the RC_{r1} and RC_{r2} designs were found to be nearly 0.75 and 0.45, respectively (Table 2.10). In sum, the results show that RC_{r1} is a more cost-efficient design than RC_{r2} in all three metrics; however, neither design can be considered feasible if only social, economic or environmental performance is taken into consideration.

Although the benefits of retrofit were calculated in different units with respect to the three sustainability metrics individually (as previously presented), a total combined benefit from all three metrics, expressed in monetary terms, was also calculated for purposes of comparison. To this end, this dissertation adopted $40 per metric ton of CO_2, the carbon price used by major international energy companies in accounting for the environmental costs and benefits of proposed projects in 2013 (CDP, 2013). This allowed us to calculate the monetary benefit from the reduction of CO_2 emissions. In the final analysis, the total estimated monetary benefit derived from reductions in fatalities, repair costs and CO_2 emissions over a 20-year planning horizon was $108,176,250 and $134,994,611 for the RC_{r1} and RC_{r2} designs, respectively (Fig. 2.7). On the other hand, the total upfront costs in monetary terms of the two retrofit deigns were obtained by summing the initial construction cost and the monetary cost of construction-related CO_2 emissions; this indicated that the BCR_r figures for RC_{r1} and RC_{r2} were 1.05 and 0.63, respectively. As shown in Fig. 2.7, for both types of retrofit design, approximately 71% of the expected benefits come from saving lives, as against 28% from reduction in repair cost, and only 1% from reduced

CO_2 emissions; these savings are not sufficient to make the retrofit actions economically feasible, if the benefits to human safety are not taken into account.

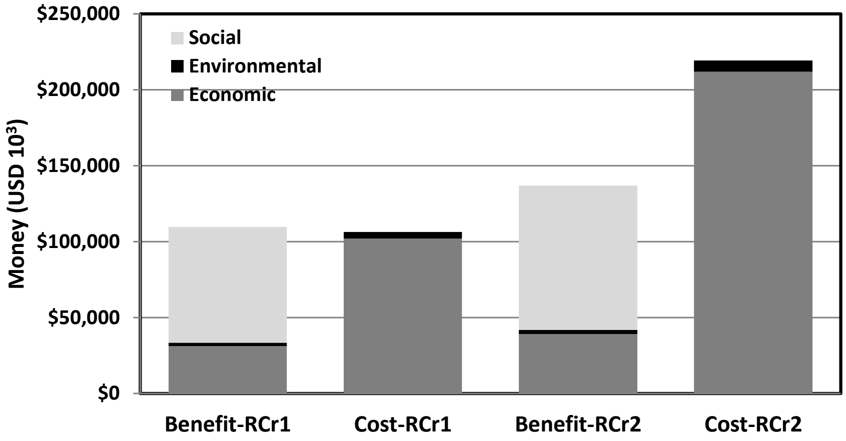

Fig. 2.7. Benefits and costs of retrofit designs (RC_{r1} and RC_{r2})

Table 2.10. Benefits and costs of retrofit designs over a 20-year period

Retrofit design	Social[a] ($\$\times10^{6}$)			Economic ($\$\times10^{6}$)			Environmental[b] (kg-$CO_2\times10^{6}$)		
	Benefit	Cost	$BCR_{r,S}$	Benefit	Cost	$BCR_{r,E}$	Benefit	Cost	$BCR_{r,EN}$
RC_{r1}	76.3	102.1	0.75	31.1	102.1	0.30	0.9	35.2	0.51
RC_{r2}	94.9	211.9	0.45	39.2	211.9	0.18	1.1	60.2	0.37

[a] The monetary value of human life used is $1 million per person (Shohet et al., 2015)

2.6 Conclusions

Contributions

Although a complete sustainable-performance analysis that takes into consideration the whole of the triple-bottom-line of sustainability has traditionally been neglected when buildings face natural hazards, the results of this study demonstrate the necessity of this type of analysis for balancing between social, economic and environmental performance in creating optimal cost-effective risk-mitigation designs based fundamentally on sustainability performance objectives. The following key contributions were made to the body of knowledge in the field of sustainable development of the built environment under natural hazards:

- Developing a comprehensive LCA framework that can incorporate building damage and convert this data into quantifiable environmental impact by means of capturing the main sources of the impact during both pre-seismic structural retrofitting and post-seismic rehabilitation.
- Evaluating the environmental value of hazard mitigation by conducting a risk-based BCA focused on building lifetime sustainability.
- Introducing a methodology that can translate seismic building damage into clearly quantifiable social, economic and environmental impacts, taking into account the use of various repair methods appropriate to each damage state as well as local economic/environmental data.

The proposed methodology was applied to two alternative retrofit designs with different costs and levels of seismic resistance. The results show that, while neither design could be considered feasible with respect to the three sustainability metrics individually, the lower-cost/lower-resistance design is justifiable if measured by the combined benefit from all three metrics, expressed in monetary terms over a 20-year planning horizon. This finding emphasizes the necessity of a complete sustainable-performance analysis in achieving a cost-effective design. The result is also partially explained by the fact that, based on the findings of our first case study, the prevention of a building from entering a state of complete damage is an effective approach for improving its sustainability performance; and the lower-resistance design is capable of preventing most buildings from being completely damaged, while the higher-resistance one provides only a small additional reduction in the number of completely damaged buildings. Additionally, this dissertation found that when considering all metrics in monetary terms, the cost-effectiveness of retrofitting actions is dominated by social benefits (number of reduced fatalities), followed by reduced repair costs and reduced CO_2 emissions.

Limitations and extensions

Followings are some limitations of this study: first, although the rehabilitation measures for building damage used in our first case study are recommended by FEMA (FEMA, 2006b), a sensitivity analysis that takes into consideration the variety of repair measures could be conducted to address the uncertainty associated with the proposed method of assessing environmental/economic impacts as a result that various repair measures may exist in practice that correspond to a level of severity of the damage; and the choice of one of these alternatives over another may involve several factors such as time constraints, availability of techniques and resources, and so forth. Additionally, the study evaluated environmental impacts solely based on the activities associated with repair of structural damage; however, the impacts attributable to damage of non-structural components and contents can be included in an extended framework. Also, more research could be done that would allow the environmental/economic benefits of reclaiming materials from demolition to be added to the present LCA framework to achieve a more comprehensive benefit-cost analysis. Meanwhile, other hazard-related recovery activities that have potentially significant environmental impacts should be included in an extended LCA framework. For instance, the extended framework could take into account land-use conversion from previously non-residential areas into residential ones, after disaster-affected areas become uninhabitable: a process that always causes considerable environmental impact in post-earthquake recovery projects (Pan et al., 2014). Finally, while the proposed methodology has here been applied to the assessment of direct losses associated with seismic damage to RC structures, it can be extended to other direct and indirect impacts, such as economic loss of building contents and displaced households considered as social loss, as well as to other building types and/or other hazards.

Implications for Practice

This study contributes to the building industry's understanding of the sustainability performance associated with natural disaster risk. Comprehensive assessment, utilizing our proposed methodology, of the effect of hazard-resistant designs on long-term sustainability performance can help decision-makers select the optimal sustainable solution based on designated performance objectives. It is hoped that the present research will serve as a basis for further studies of the long-term sustainability of performance-based designs (new or retrofit) for buildings confronting natural hazards, with the wider aim of achieving optimal cost-effective designs.

Chapter 3: Assessment of Risk Concentration of Urban Areas under Natural Hazards

3.1 Abstract

This study first thoroughly reviewed both engineering-based and social science-based approaches for assessment of natural hazards risk of urban areas. The natural hazards risk assessments using engineering-based loss estimation modeling usually focus on probabilistic assessment of damage to and losses from the constructed facilities; the social science-based approaches investigate the social and/or system resilience of exposed people and critical infrastructures. A key conclusion that emerged from assessing the existing literature is that these two approaches remain greatly separated and thus they should be integrated to be taken into account interactively. The following key contributions were made to the body of knowledge in the field of natural disaster risk assessment of the built environment: (1) developing a comprehensive framework for assessment of natural disaster risk by integrating physical impacts, system resilience and social resilience of an urban area; and (2) introducing a methodology that can identify relatively risky area at community level by means of capturing the interaction between physical impact and socio/system resilience.

The proposed methodology was illustrated by a case study in the city of Tiberias for assessing its seismic risk. The results show that, with regard to the risk associated with the interaction between building damage and social resilience, the lower social resilient households are less vulnerable to building damage in Tiberias due to local characteristics of the distribution of building classification. The result is also shows

that, with regard to the risk associated with the interaction between fatalities and system resilience, the lower system resilient households are more vulnerable to fatalities loss. This finding suggests that the medical resources are allocated and transportation access is achieved unevenly by different census tracts in the city. As a result, more emergency medical resources and transport access should be placed in those areas with low system resilience since they are expected to subject to relatively serious fatalities loss. This study contributes to the natural hazards management communities' understanding of the integration of physical impact, system and social resilience for identifying risk and the landscape inequality in the capacity of responding to and recovering from the risk.

3.2 Introduction

Recently, destruction of modern built environments resulting from natural disasters has increased due to the repercussions of climate change as well as human-related activities, such as rapid population growth, urbanization in hazard-prone areas. Reduction of urban natural disaster risk has become major global concern for the sustainable development of urban areas. Accordingly, several risk assessment tools have been developed for evaluating and identifying the level of risk and thus according risk reduction plans can be made and their effectiveness can be assessed. Traditionally, research on natural disaster risk assessment has been divided into two major distinct approaches: engineering-based and social science-based (Brink and Davidson, 2014). With advanced understanding of underlying physical mechanisms controlling the behavior of natural hazards, as well as failure mechanisms of physical vulnerability of built assets subjected to natural hazards, engineering-based approaches have focused on damage of constructed facilities and estimation of direct loss during disasters. On the other hands, arguing that the risk of society under hazards is not solely dominated by the interaction of hazards and built environment, social science-based studies have attempted to investigate the social vulnerability/resilience of a community or city to hazards – capacities of exposed people and communities to copy with and recovery from losses. Nevertheless, due to the complex multifaceted nature of social vulnerability, questions still remain as to standard guidelines for quantifying social resilience to meaningful and operational metrics for evaluating the effectiveness of practical risk reduction decision. Overall, neither engineering-based, nor social science-based approach can comprehensively evaluate the disaster risk of a community, insofar as either one of them can only explain the effects of vulnerability of an element at risk from a narrow specific point of view.

Realizing that the risk of a community to natural hazards is a far more encompassing concept than that of either physical vulnerability or social resilience only, in order to comprehensively estimate loss caused by hazards, this dissertation introduces a new multi-disciplinary framework that extends engineering-based risk estimation framework to include social resilience. Moreover, considering the crucial role of critical infrastructure of a urban system in disaster response, the proposed framework also include the resilience of critical infrastructure. Overall, the proposed framework takes into account 1) physical vulnerability of built structures, which dominate short-term loss; 2) system resilience of critical infrastructure, which determine capacity of emergency response; and 3) social resilience, which favors capacity of recovering from long-term loss. Furthermore, not only the physical vulnerability of built environment, system resilience of critical infrastructure, and social resilience of residents can be evaluated individually, but the interaction between these factors can also be investigated.

Attempting to comprehensively assess the multifaceted vulnerability and resilience of an urban system, with the expectation of development of an operational tool for risk control decision-making support, mainly two areas have promoted in the disaster risk management community: (1) conceptual frameworks for comprehensively capturing and assessing vulnerability and resilience; and (2) methodologies to integrate multifaceted vulnerability and resilience for an operational metric in risk management practice. Working on the former has led to awareness of variety of factors on the extent of natural disaster risk, including physical factors such as potential intensity, and frequency of future hazard events, resistance to hazards of buildings, and social factors such as wealth, and health conditions of exposed people. On the other hand, studies in the second area have aimed to determine operational metrics for the purpose of risk identification and communication in risk reduction decision-making support. The majority of such studies have widely employed an single index or score (Kleinosky et al., 2007), which is always composed of various factors with different units, to identify the relatively risky areas where risk reduction action needs to be performed. In addition, rather than aggregating different factors into a single index, some studies have also examined spatial relationship between these factors. For instance, they superimposed social and physical vulnerability on a same map to highlight the spatial relationship among social and physical factors

(Dewan, 2013) (Felsenstein and Lichter, 2014) (Koks et al., 2015). Nevertheless, although operational, either the use of index, or of spatial correlation, cannot severe as a meaningful metric for risk reduction action decision-making support. Therefore, with the intention of discovering the role of comprehensive vulnerability of a urban system to natural hazards, this study aims to 1) develop a comprehensive framework for assessment of natural disaster risk by integrating physical impacts, system resilience and social resilience of an urban area; and 2) introduce a methodology that can identify relatively risky area at community level by means of capturing the interaction between physical impact and socio/system resilience. Following the development of framework, a case study is conducted to illustrate the application of the proposed methodology to the evaluation of the seismic risk in an urban area, and to the determination of corresponding risk reduction actions. The present methodology is hoped to serve as a basis for further studies aimed at assessing urban natural disaster risk, and determining effective hazard-mitigation strategies.

3.3 Literature Review

3.3.1 Definition of Terminology

The existing terminologies used in most studies in disaster assessment, such as “risk”, “vulnerability,” and “resilience,” have been widely expressed and used in other various scientific fields. Since various researchers from different backgrounds have made their own definitions for their specific interest and purpose, confusion is often seen when a definitions crosses disciplines. For instance, the term vulnerability signifies the physical resistance of built assets to hazards in the world of engineering; however, this term always represents social-economic conditions of a social unit in the realm of social science. Among several studies that have attempted to clear up such confusion, although none of them successfully makes a universal definition, the glossary proposed in the report by United Nations International Strategy for Disaster Reduction (UN/ISDR, 2004a) is considered as a relatively broadly accepted and useful starting point for definitions in the community of disaster risk management (Schneiderbauer and Ehrlich, 2004a). The definitions proposed in this study mainly refer to those defined by UN/ISDR, along with some refinements from other studies.

Hazard

Hazard: "A potentially damaging natural physical event, phenomenon and/or human activity, which may cause loss of life, property damage, economic disruption and/or environmental degradation. Hazards can be single, sequential or combined in their origin and effects."

After: (UN/ISDR, 2004a) and (Schneiderbauer and Ehrlich, 2004a)

The term 'hazard' and 'risk' are often used interchangeably; however, it is generally accepted that risk is an expected probability of loss, usually assessed by computational models, of exposed elements to a certain hazard; hazard is an event that has potential to cause loss to the elements and serves as one of the inputs of the risk assessment models (the other crucial input is elements' vulnerability that influences to what degree the loss would be). In the study, this dissertation used the definition of hazard that originally proposed in UN/ISDR (UN/ISDR, 2004a) and revised by Schneiderbauer and Ehrlich (Schneiderbauer and Ehrlich, 2004a), which embraces the crucial determinants of hazard, such as 'the potential to cause loss' and 'physical event and/or human activity.'

Exposure

Exposure: “The built environment (buildings, infrastructure etc.), natural environment (geography, ecosystems etc.), and social environment (people, community etc.) of the element located within hazard zone”

Since the vulnerability of an element at risk mainly depends on its exposure, some scholars tend to consider exposure as part of vulnerability. However, this study sees exposure and vulnerability as separate concepts and they will be used as two components in the loss estimation model that will be explained later. Built, natural and social environment of the exposed element have different vulnerability to hazard. For instance, masonry buildings are likely to be more vulnerable to earthquakes than wooden built ones; however, the converse is also true when tornados are considered as given hazard (i.e. wooden buildings are likely to be more vulnerable to tornados than masonry built ones).

Vulnerability

Vulnerability: “The conditions of a social unit, resulting from physical, social, economic, and environmental factors, in terms of their capacity to anticipate, resist, cope with, and recover from the impact of hazards.

After: (UN/ISDR, 2004a) and (Schneiderbauer and Ehrlich, 2004a)

Risk

Risk: “The probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between given hazards and vulnerable conditions of the exposed element during a certain period of time."

After: (UN/ISDR, 2004a)

In these definitions, the words *probability/possibility* and *consequences/loss* are frequently observed and emphasized as two main determinants of risk. In addition, risk is often referred to a given *hazard* to a given *element* over a specified *time period*. Therefore, this dissertation encompasses these determinants in our definition including 'probability,' the reference to a specified hazard, exposed element and time period. The possible negative consequences can be in terms of social, economic and/or environmental.

3.3.2 Paradigm Shift of Risk and Vulnerability Research in Natural Disaster

Hazard-based risk assessment

Risk is usually determined in this approach as the intensity of a hazard at a certain site and during a certain period, or the loss associated with certain level of intensity resulted from historical loss data. In seismic risk studies, the basic seismological characteristics of an earthquake itself: most likely locations of future events, their magnitude, and their frequency of occurrence are first addressed. These three elements are closely relevant and, assuming there are regular repetitions of the same rupture event, the Gutenberg-Richter magnitude distribution is usually used to model the relationship between the magnitude of earthquakes and their frequency of occurrence as a combination of so-called characteristic earthquakes (Grossi et al., 2005). In addition to the seismological characteristics, the exposed site conditions need to be taken into consideration to estimate the physical impact of earthquakes to the affected area. For instance, taking into consideration the epicenter-to-site distance, source rupture mechanisms and social conditions, attenuation equations, which mathematically describes the rate at which the amplitude of the seismic waves decreases as the waves propagate outward from the epicenter (Grossi et al., 2005), are commonly used to transfer the magnitude of an earthquake to the intensity of the earthquake at particular affected sites. For instance, ShakeMap, developed by the United States Geological Survey by capturing actual patterns and trends in the propagation of seismic waves, represents the ground shaking produced by an earthquake in a certain area as contour maps of PGA, PGV, or spectral response at certain periods (Kircher et al., 2006b). Although this type of hazard maps usually serves as a useful tool for rapidly identifying the expected degree of ground shaking following significant earthquakes in affected area, but it does not provide estimates of associated damage and loss (Kircher et al., 2006b).

In high seismicity areas where data of post-earthquake loss surveys are available, the seismic losses can be statistically estimated as loss-intensity functions (loss is a function of seismic intensity) based on the damage and losses observed after earthquakes. Along with hazard maps, empirical loss-intensity functions can help rapidly identify the estimated losses at a certain seismic intensity in the affected area following earthquakes (Samardjieva and Badal, 2002) (Wald et al., 2006) (Erdik et al., 2011). Similarly, using recorded data, structural vulnerability functions or fragility curves of buildings can be assessed and derived from the observed structural damages during earthquakes (Barbat et al., 1996) (Dolce et al., 2003). It is worth noting that a well-recorded post-earthquake database, which can only be founded in the area with high seismicity, is necessary in applying such hazard-based approaches; otherwise, local expert opinion would be used for supporting or replacing the incomplete observed data (Barbat et al., 2010).

Physical vulnerability-based risk assessment

Physical vulnerability-based approach to seismic risk assessment is mainly to determine building seismic damage by investigating the interaction between seismic hazards and building physical vulnerability. In the earlier studies of the evaluation of the physical vulnerability of structures, due to the lack of fully understanding of structural seismic response, qualitative descriptors are used to describe and classify the buildings into vulnerability classes such as low, medium, or high (Barbat et al., 2010). Similarly, without analytical models to describe the structural seismic mechanism, the vulnerability index method is obtained based on past damage survey data and the corresponding information of the parameters of the building which could influence its vulnerability, such as type of foundation, structural design and the construction practice of the building (Barbat et al., 2010). Such indices are then calculated as a function of scores attributed to the aforementioned structural characteristics to reflect the seismic quality of a building. Both qualitative descriptors and vulnerability indexes are classified as an empirical method due to the need of past damage data and are seen as ‘indirect’ method to calculate the seismic damage because the relationship between the seismic intensity and the corresponding structural response is established through an index (Calvi et al., 2006).

Instead of the use of macro-seismic intensity or peak ground acceleration (PGA), capacity curves, which are force-displacement spectral ordinates corresponding to the first mode maximum response of structures, are used to determine the structural seismic behavior by means of nonlinear structural analyses. Depending on demand spectrum, the fragility curves can be obtained, which are an estimate of the cumulative probability of being in, or exceeding a given damage state for the given level of ground shaking (FEMA, 2013). Compared to empirical methods, this analytical method tends to characterize more detailed vulnerability assessment algorithms with direct physical meaning (Calvi et al., 2006).

Once the building damage is obtained by interpreting structural seismic response in physical vulnerability using either empirical or analytical methods, seismic loss models are then employed to estimate the losses due to damaged buildings in certain damage states (i.e. none, slight, moderate, extensive or complete). For example, the number of casualties during earthquakes can be estimated based on the assumption that there is a direct relationship between building damage states and numbers of casualties – this relationship is often referred to as the casualty rate (Spence and So, 2011). In economic loss assessment, costs of repairing and replacing damaged structures is generally estimated and served as main contribution to the seismic economic loss (FEMA, 2012). Similarly, the environmental losses can also be estimated by the energy or CO_2 consumption attributable to the repairing and replacing work to damaged structures (Hossain and Gencturk, 2014) (Wei et al, 2015). All these models see losses as primarily a function of direct physical damage of building. However, although building damage are mainly responsible for the casualty loss (Spence and So, 2011), the degree of long-term economic and environmental losses would be controlled by other broader factors from the social and human dimensions of an affected community, which would aggravate the resulting losses (Blaikie et al., 2014) (Barbat et al., 2010) (Lin et al., 2015).

Social vulnerability-based risk assessment

Arguing that the vulnerability of society to hazards is not only dominated by engineering approaches (i.e. building physical vulnerability), the political ecologist interprets vulnerability within society in socioeconomic structures that control individual and group action (Hewitt, 1983) (Watts, 1983). These political ecologists see the vulnerability as a lack of entitlement (Adger, 2006) and attempt to explain how the social conditions, such as poor and marginalized, make people exposed to natural hazards and reduce their capacity for coping with hazards (Hewitt 1983). In this regard natural hazards can be seen as a social construction in which different individual and group are differentially exposed to potential risk with possessing differential coping capacities (Kasperson et al., 2005). Following this logic, vulnerability is linked to economic and political impoverishment and thus studies focuses on why and what makes social units impoverished. For instance, Marxian class theory or, more broadly, critical approaches are used to explain the sources and causation of the lack of entitlement as the outgrowth of exploitation resulted from capitalism. The more exploitation makes social units more marginal economically and the weaker politically, in turn the more are they exposed to hazards and the more difficult for them to cope with perturbations (Wisner, 1988) (Wisner and Luce, 1993).

Meanwhile, several factors have been found to contribute to social vulnerability to natural hazards. For instance, economic development could play an important role on shaping socioeconomic vulnerability (Cutter et al., 2003) (Rashed and Weeks, 2003). By investigating the relationship between poverty and disasters in the US, (Fothergill and Peek, 2004) indicates that: ”socioeconomic status is a significant predictor that the poor are more likely to perceive hazards as risky; less likely to prepare for hazards or buy insurance; less likely to respond to warnings; more likely to die, suffer injuries, and have proportionately higher material losses; have more psychological trauma; and face more obstacles during the phases of response, recovery, and reconstruction.” On the other hand, from the rational choice perspective, the elite have greater economic incentive to conduct disaster reduction for saving their lives and valued property (Kahn, 2005). Other widely used factors for determining social vulnerability include gender, age, race and disability (Fordham, 2003) (Felsenstein and Lichter, 2014) (Noriega and Ludwig, 2012) (Lin et al., 2015). These factors are intertwined in complex social processes presenting in the form of unbalanced urban development (Pelling, 2003), socioeconomic inequality (Anbarci et al., 2005), or lack of social networks and support mechanisms (Klinenberg, 2003), which influence the vulnerability that is irrespective of the type of hazards (Schneiderbauer and Ehrlich, 2004b) (Lin et al., 2015). However, due to the complex process and variety of composition, it is difficult for social vulnerability to be qualified and used to model its impact to disaster risk in terms of quantifiable losses. Although, due to their multifaceted nature, indicators or indexes are commonly used as a combination of various components attributable to social vulnerability, questions still remain as to standard guidelines for assessing each component individually, and of methodology to link components to gather final metrics for resulting risk assessment (Villagrán de León, 2006).

Composite vulnerability-based risk assessment

Realizing that the vulnerability is a far more encompassing concept than that of either physical or social vulnerability only, several studies attempt to conduct comprehensive multi-disciplinary assessment that takes into account not only physical vulnerability of built structures, which dominate direct damage and losses, but also the social vulnerability, such as socioeconomic condition and community resilience, which favor the indirect impacts and recovery capacity (Smith, 2004) (Rygel et al., 2006) (Flanagan et al., 2011). Considering the risk is the product of hazard, exposure and vulnerability, a composite risk index is designed to conclude the factors contributing to these three risk components. Factors including population at risk, hazard intensity, site condition and land use are commonly used to evaluate the contribution from hazard and exposure components to risk (Koks et al., 2015). In regard to evaluation of physical vulnerability to natural disaster, building types and built year are the most common factors (Lin et al., 2015) and these factors are able to be quantified in terms of e.g. structural fragility and further used to calculate corresponding building damage and associated losses.

By contrast to the scandalized physical vulnerability indicators, there is neither standardized unit for social vulnerability. Moreover, unlike some common scales used in physical loss models such as number of buildings damaged, number of casualties, or dollars of direct economic loss, there are no such measurable scales for the losses correlated to social vulnerability (Brink and Davidson, 2014). In other words, the risk attributable to social vulnerability cannot be well qualified and measured due to the unclear mechanism between them and the unitless of social vulnerability itself. In many studies using composite index for assessing the degree of risk, indicators of social vulnerability is linearly combined with those of physical vulnerability and those attributed to hazard and exposure. However, after linear combination, the units of the indicators of physical vulnerability are not retained, but rather are normalized to make them unitless and commensurate with social indicators (Davidson, 1997) (Rashed and Weeks, 2003) (Chakraborty et al., 2005) (Walker et al., 2014).

The other issue of linear combination of social and physical vulnerability arises from the different natural within them. Generally, physical vulnerability is hazed-dependent and used to describe buildings' resistance to the impact of a given hazard. More important, it can be used to directly calculate the losses due to the given hazards. In contrast, social vulnerability is more like to be hazard-independent, which describe general social-economic condition of a society (Schneiderbauer and Ehrlich, 2004b) (Wisner et al., 2004). As a result, it makes little sense to linearly combine social vulnerability, being hazard-independent, with hazard-independent indicators and also hazard indicators. Moreover, given the definition of vulnerability, it is necessary to specify 'who is vulnerable to what (hazards)?' so that the associated risk can be evaluated. Although the usage of the term 'general-vulnerability' or 'overall-vulnerability' (Kleinosky et al., 2007), regardless the type of hazards, signifies that different vulnerabilities can be individually evaluated and then aggregated (Fekete, 2010), their application on the assessment of risk due to a certain of hazard remain unclear. Instead of aggregating all different indicators from social and physical vulnerabilities to single index, some studies have examined spatial relationship between the indicators. They superimposed social and physical vulnerability on maps to highlight the spatial variation in the disaster risk of each area (Dewan, 2013) (Felsenstein and Lichter, 2014) (Koks et al., 2015). However, since there is no one measurable index that can be used to compare the degree of risk of different area, the application of the result on risk management practice remain lack.

3.4 Methodology

3.4.1 Risk Equation

In the field of natural disaster science, although risk measurement differs according to the purpose of interest of analysis, the definition of risk as the potential loss resulting from the interaction between three components – hazard, exposure and vulnerability – has been widely accepted and applied in disaster assessment research (see (Rashed and Weeks, 2003) (Cardona, 2004) (ISDR, 2004) (Grossi et al., 2005, UN/ISDR, 2004b) (Grossi et al., 2005) (Kron, 2005) (Birkmann, 2007)) and it can be expressed as Eq. (3.1). For instance, (Grossi et al., 2005) developed the catastrophe model for assessing the loss by overlapping these three components, as shown in Fig. 3.1. Similarly, this definition was also visualized as the 'risk triangle,' shown in Fig. 3.2.

$$\mathit{Risk} = \mathit{hazard} \times \mathit{exposure} \times \mathit{vulnerability} \tag{3.1}$$

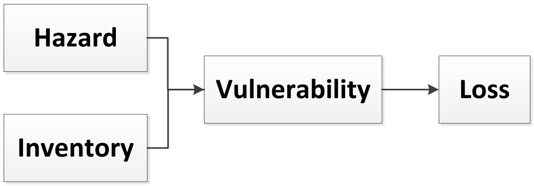

Fig. 3.1. Catastrophe risk model (modified from Grossi et al., 2005)

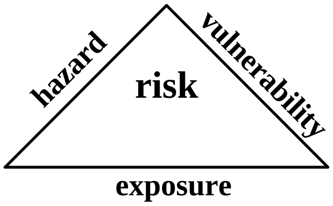

Fig. 3.2. Risk triangle

This definition of risk has also been widely used for identification of risk mitigation actions. Different risk mitigation actions, primarily including risk avoidance, reduction, transfer and acceptance, focus on reducing the impacts of different component(s). For instance, risk avoidance is to reduce the impact of risk by the means of shunning the exposure at risk, as depicted in Fig. 3.3, through actions such as urban plans by not allowing properties to be built on the areas at risk. The risk will equal to zero if all elements are shunned form hazards, i.e. the effect of exposure component become zero while the effects of other components remain the same. Also shown in Fig 3.3, another common countermeasures of risk management is to reduce the vulnerability of building stock by retrofitting structures to higher standard (Erdik et al., 2010). However, risk reduction can also be conducted by non-engineering means to lower social vulnerability such as enhancement in public education and awareness of risk (Nirupama and Maula, 2013) (Siagian et al., 2014).

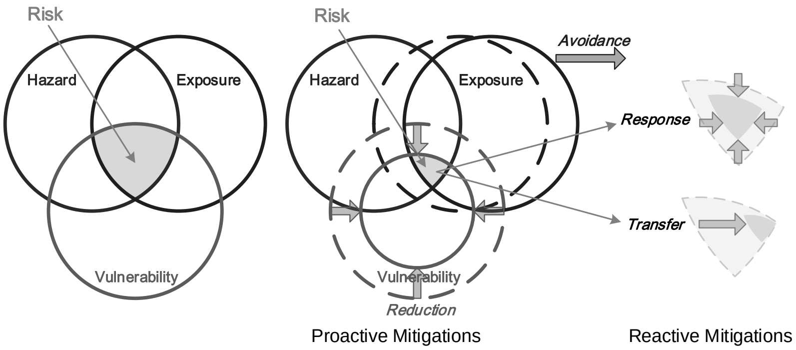

Fig. 3.3. Risk management

In a general risk management study, following the identification and estimation of particular types of loss of interest given hazard scenarios, the effectiveness of corresponding mitigation action can be recognized by investigating the degree of the loss reduced by the action. Additionally, for public policy making, the desirability of a particular hazard-mitigation action is also analyzed by comparing the benefits associated with the reduction in losses against the upfront cost of the mitigation. Take earthquake as an example, estimated number of casualties is a crucial information for emergency hospital capacity, or expected building damage is usually served as the basis for homeowner seismic insurance policy.

In a general seismic risk analysis, loss is estimated by direct physical damage and induced damage. Direct physical damage is the structural damage to built-objectives such as building or infrastructure for in given level of ground shaking, and the induced damage is defined as the consequences made by secondary impact of the earthquakes such as following fire or hazardous materials release (Kircher et al., 2006b). Several models have been developed for the evaluation of the direct physical damage by following the concept of Eq. 3.1. For instance, HAZUS calculate building damage via fragility curve that are composed of building capacity curve (vulnerability) and demand curve (hazard and exposure).

Loss, caused by both direct and induced damage, and it is divide into “direct” and “indirect” categories (Kircher et al., 2006b). Direct losses are defined as those caused immediately by the damage of built environment, such as building damage repair costs, number of casualties, or number of displaced households. On the other hand, indirect loss includes the broad and long-term implications of direct impacts, for example, business interruption or changes employment profile in the affected area (FEMA, 2013). Although indirect losses often play a crucial role in post-event recovery planning, it is difficult to estimate indirect losses due to the difficulties of collecting post-event loss data and of quantifying their long-term effects, which may take years to appear and even longer to be properly understood (Bird and Bommer, 2004). However, it is reasonable to assume that indirect loss is directly proportional to direct loss, i.e. greater direct loss cause greater indirect loss and vice verses. For example, (Carreño et al., 2007) estimate the total risk based on the direct effects and expressed the indirect effects as a factor of the direct effects, known as the Moncho’s Equation in the field of disaster risk indicators.

Unlike indirect loss, several seismic loss models have been developed to assess direct loss. For example, the number of casualties during earthquakes can be estimated based on the assumption that there is a direct relationship between building damage states and numbers of casualties – this relationship is often referred to as the casualty rate (Spence and So, 2011). In economic loss assessment, costs of repairing and replacing damaged structures is generally estimated and served as main contribution to the seismic economic loss (FEMA, 2012). Most of those models see losses as primarily a function of direct physical damage of building for following basic reason: it is building that is vulnerable to earthquakes but not human beings; human beings are vulnerable to the building damage caused by earthquakes, i.e. building kills people but earthquake does not. For instance, (Spence et al., 2011) concluded that almost all the casualties in earthquakes are resulted from damaged building by investigating casualty data from several historical earthquakes. Therefore, the predication of building damage is at the heart of estimates of earthquake losses (Kircher et al., 2006b).

3.4.2 Risk Assessment

Fig. 3.4 shows how the different types of loss are estimated by its risk triangle and Fig. 3.5 shows the flow chart how the direct and indirect losses are assessed by physical and social vulnerability individually. Fig. 3.6 presents the risk concentration assessment framework that creates the basis for a set of three matrices which are a vulnerability and resilience assessment tool. The framework reflects a desire to provide an interpretation of the relationships between different levels of vulnerability with a prevention orientation. The framework and related tool provide a basis for an integrated assessment of vulnerability before an event strikes, thereby aiding decision-makers and citizens to take appropriate anticipatory and mitigation measures. The framework attempts to capture the most relevant features of vulnerability and resilience but is, inevitably, based upon an expert selection of aspects considered as important and representative of reality. Physical vulnerabilities are mainly addressed at the household scale but systemic vulnerability can only be appropriately considered by linking the household scale to a regional scale. For recovery capabilities and resilience, all scales are taken into consideration.

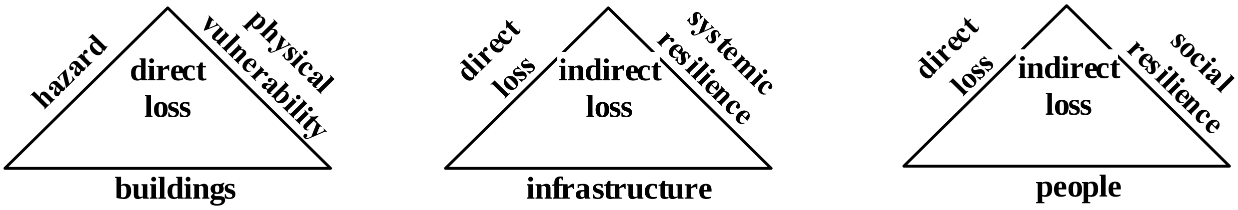

Fig. 3.4. Risk assessment for direct and indirect losses

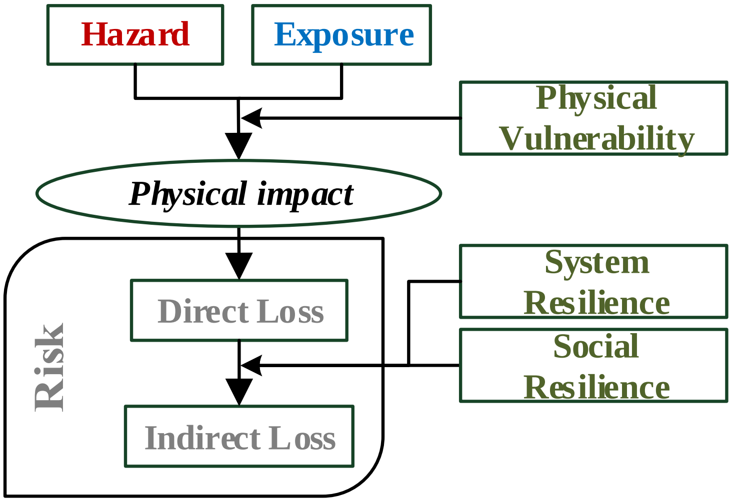

Fig. 3.5. Risk assessment flowchart

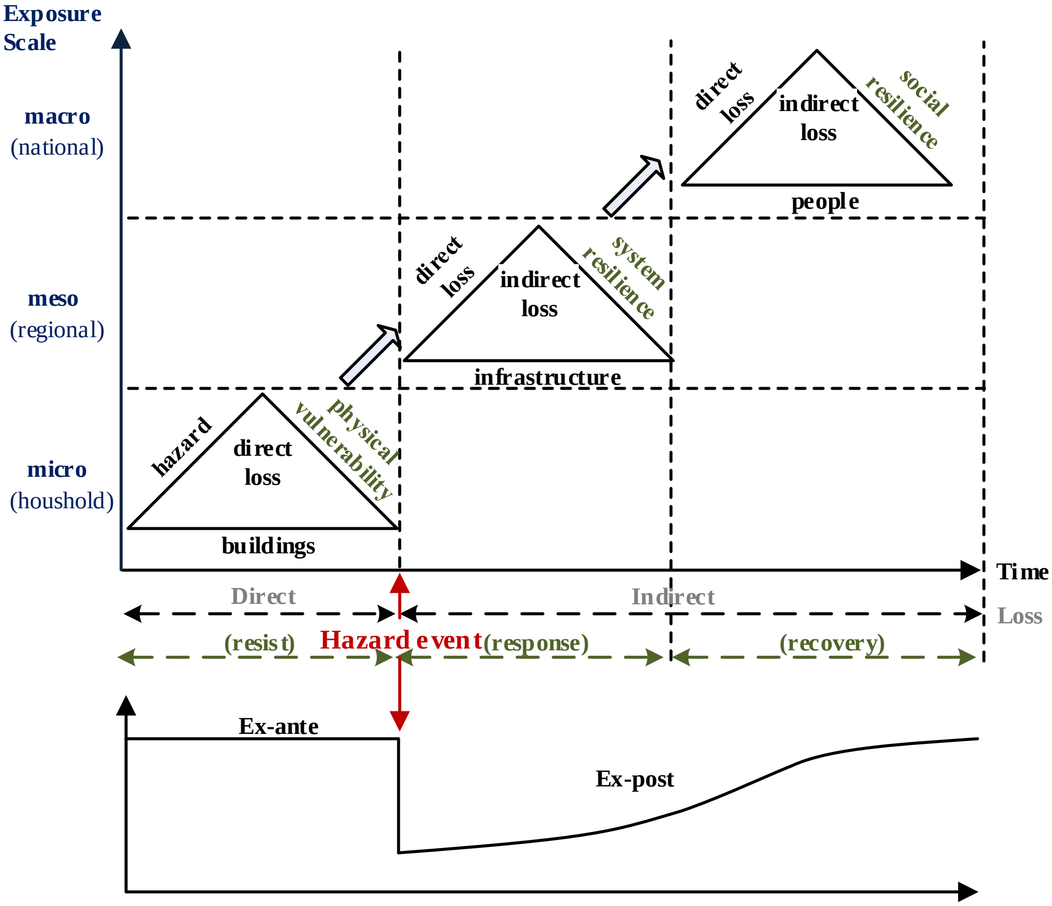

Fig. 3.6. Risk assessment process

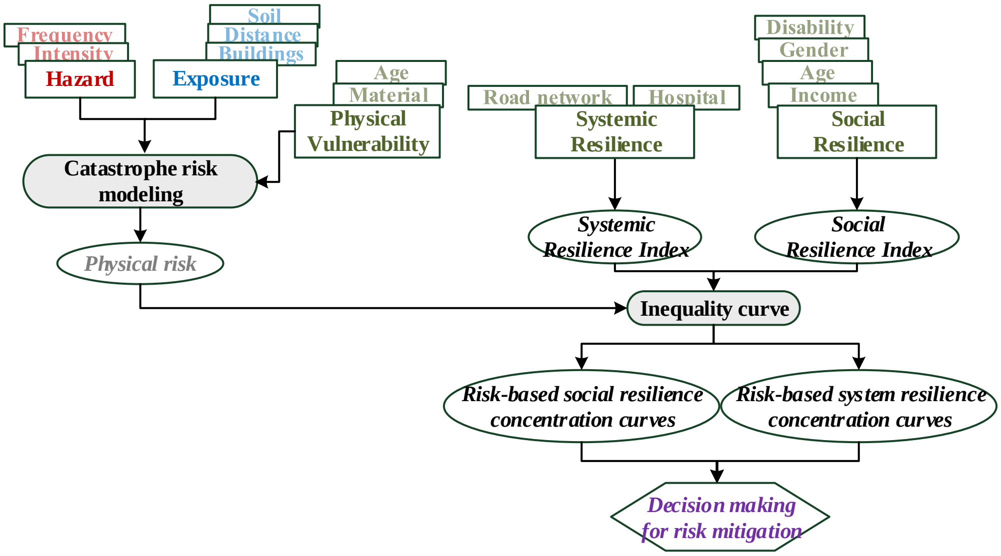

Fig.3.7. Flowchart of risk assessment

3.4.3 Analysis of Physical Vulnerability and Impacts

As shown in Fig. 3.8, Earthquake loss assessment models have played an important role in engineering design for natural hazards. For instance, structural engineers design buildings using particular probability of exceeding of the later forces by winds or earthquakes. Furthermore, these models have been developed to assess the casualty or economic losses caused by the damage of buildings result from natural hazards. The four basic components of an earthquake loss model are: hazard, inventory, vulnerability, and loss. First, the hazard module characterizes the risk of the natural hazard phenomena itself. For instance, an earthquake hazard is characterized by its relevant parameters like soil condition, epicenter location and moment magnitude. Meanwhile, the frequency of certain magnitudes or frequencies of earthquakes are needed to investigate. Second, the inventory module characterizes the inventory of properties at risk (Fig. 3.9). One essential parameter to describe the inventory is location of inventory at risk. Moreover, in order for more accuracy of the estimate, factors describing building attributes can be also considered, such as structural type, the height, the age of buildings. Next, in the vulnerability module, the vulnerability of the inventory to damage is calculated from the result of the hazard and inventory modules. For example, the HAZUS program classifies structural damage in four damage states: Slight, Moderate, Extensive, and Complete state. Meanwhile, fragility curve of a building is used to represent its vulnerability to damage. In order to estimate economical loss, factors like its contents and also time element losses, such as business interruption loss or relocation expenses, can be added in the model. Finally, in the loss module, loss could be classed as direct or indirect. On one hand, direct losses could include human casualties, or cost to repair a building, whose loss can be calculated directly by the level of damage. On the other hand, examples of indirect losses are business interruption impacts and relocation costs of residents, which can be considered as consequences due to the damage. In general, indirect losses are more difficult to qualify than direct ones.

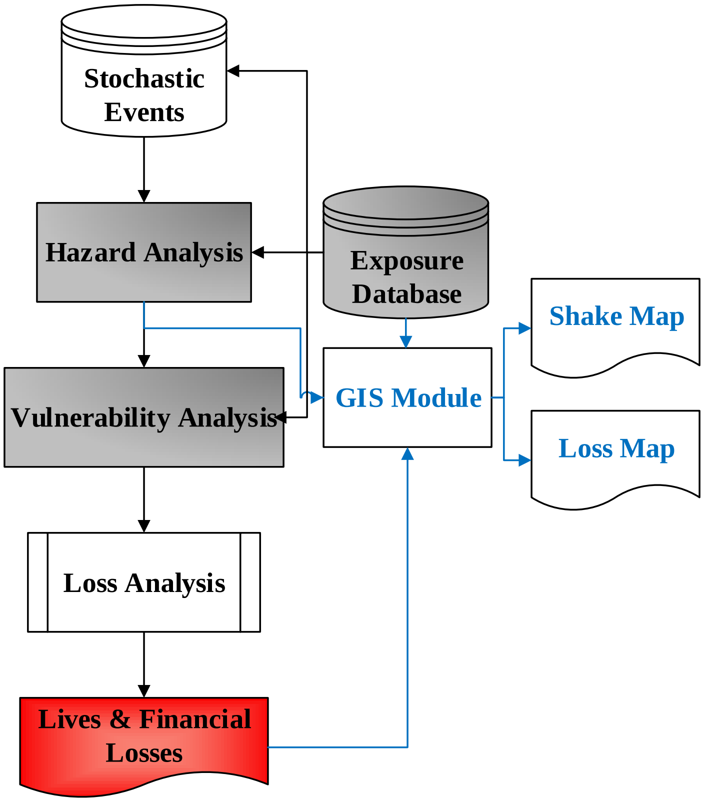

Fig. 3.8. Earthquake loss assessment model

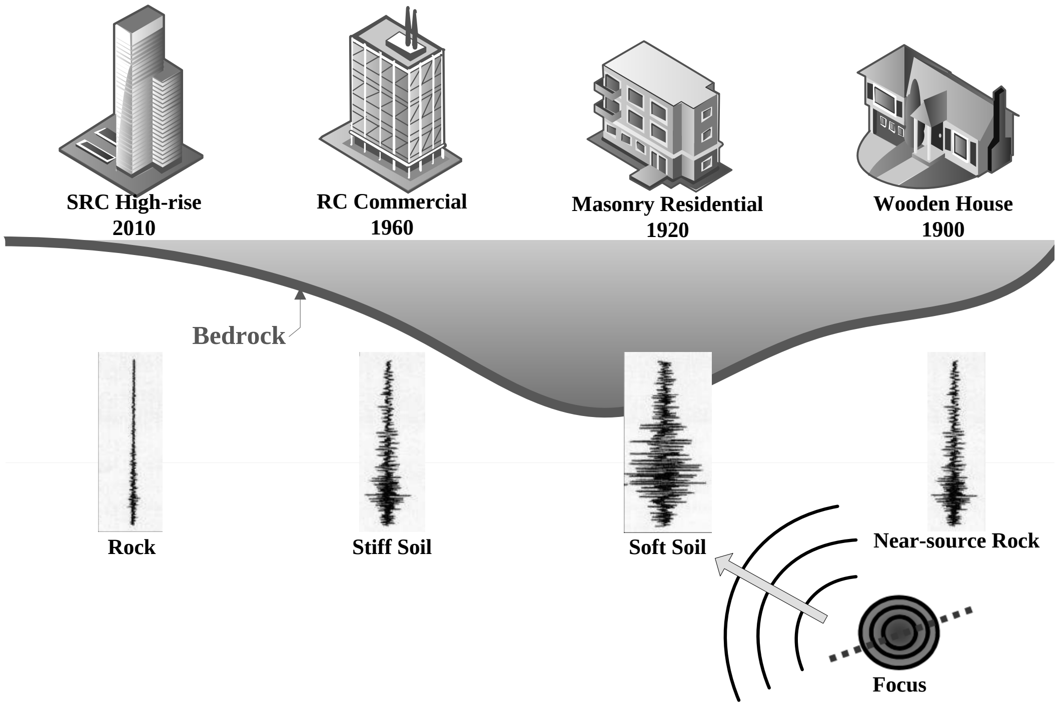

Fig. 3.9. Attenuation and local soil/site effects

3.5 Case Study

3.5.1 Assessment of Social and System Resilience

Demographic statistics and socio-economics status

The city of Tiberias is comprised of 12 census tracts (Fig. 3.10) with a total of 13,235 households and 42,079 inhabitants (according to the 2008 Israel national census survey conducted by the Central Bureau of Statistics). To determine the Social Resilience Index of each census tract, this dissertation has examined the demographic characteristics, including household incomes, age, gender, education level, percentage of people with disability, and ownership of housing. As shown in Fig. 3.11, the average household incomes of census tracts are unevenly distributed in the city. The incomes of the census tracts 11 ($179,447) and 24 ($213,051) are greatly above the average national level ($151,234); however, the average incomes of census tracts 14, 33, and 34 are below $100,000, which are approximately only half of the richest census tract in the city. Observing Fig. 3.12, showing the percentage of male and female population of the city, we find that the male and female population is quite equally distributed among all census tracts, except for the census tract 15 and 22. The distribution of age is shown on Fig. 3.13. Fig. 3.14 represents uneven distribution of people's education levels among different census tracts. Approximate one third of the people in the census tract 28 and 31 received higher education (tertiary degree), but only seven percent of people in tract 36 have higher degrees. Overall, the average percentage of population with higher education is highly below the national average percentage of 46%. Fig. 3.15 shows the percentage of homeownership in each census tract. Interestingly, the distributions of homeownership do not follow those by household income – generally speaking, wealthy households can more afford to own their houses, and poor people cannot afford to have a own house. For instance, 92% people in tract 15 have their own house, which is the highest percentage comparing with all other census tracts; however, the average household of the tract are ranked the seventh over all 12 census tracts. Fig. 3.16 shows the percentage of people with disability, which is defined as those people who are unable to perform normally in daily life, such as walking, hearing, seeing, having memory problems, or taking shower and dressing independently. Using Eq. (3.3), the normalized social resilience index can be calculated and the results are shown in Fig. 3.18. From Fig. 3.18, we can indicate those tracts with relative low SRI (below 0.25), including tracts 33 and 34. Tracts 3 and 34 are also identified as those with relative poor and less people with higher education (Fig. 3.18).

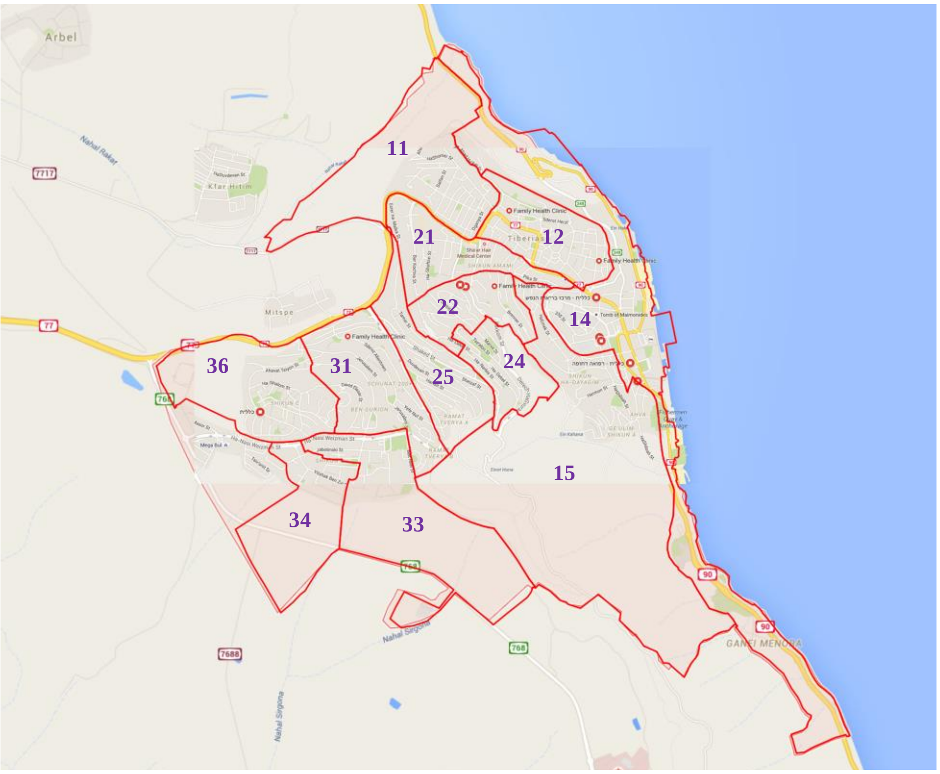

Fig. 3.10. Map of Tiberias

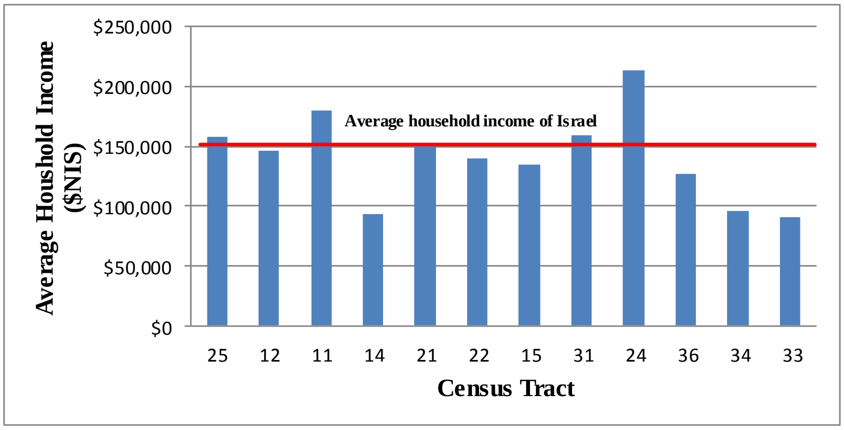

Fig. 3.11. Average household income of Tiberias

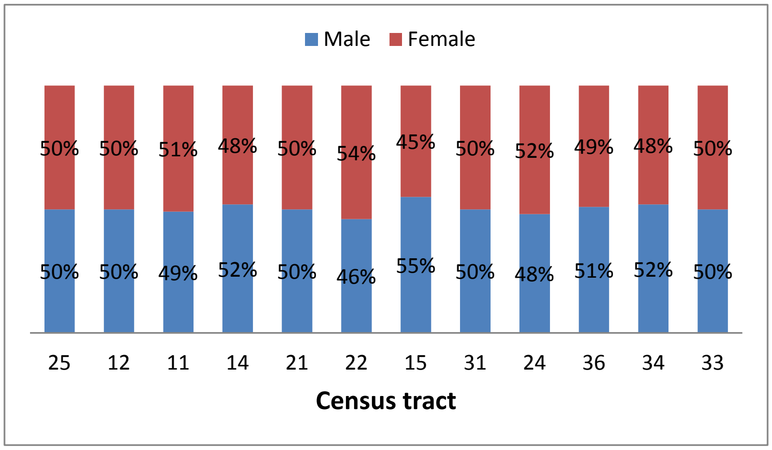

Fig. 3.12. Percentage of male and female population of Tiberias

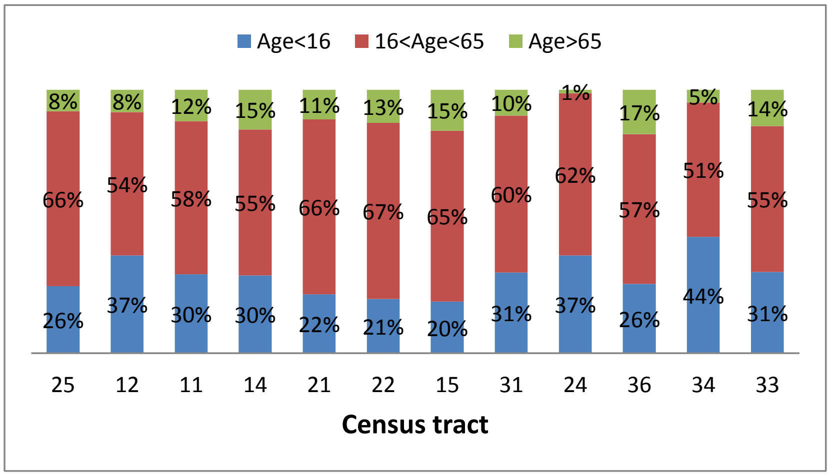

Fig. 3.13. Age distribution of the population of Tiberias

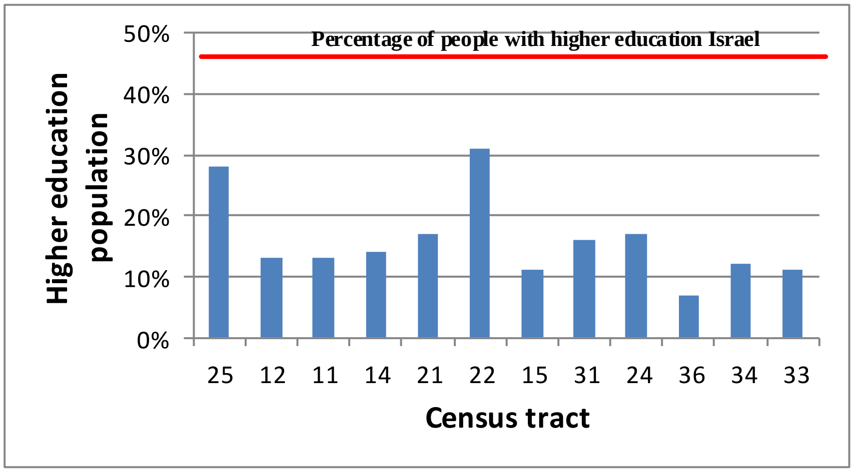

Fig. 3.14. Percentage of people with higher education

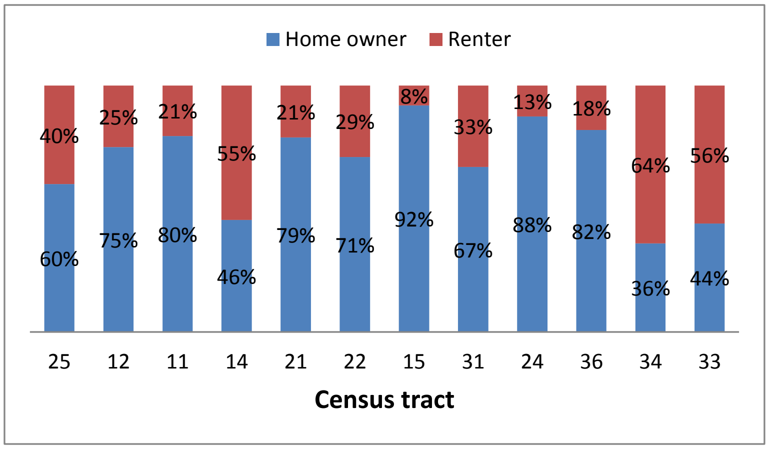

Fig. 3.15. Percentage of homeownership

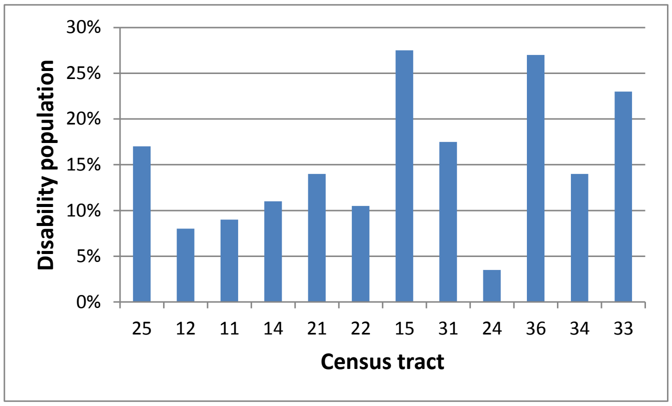

Fig. 3.16. Percentage of people with disability

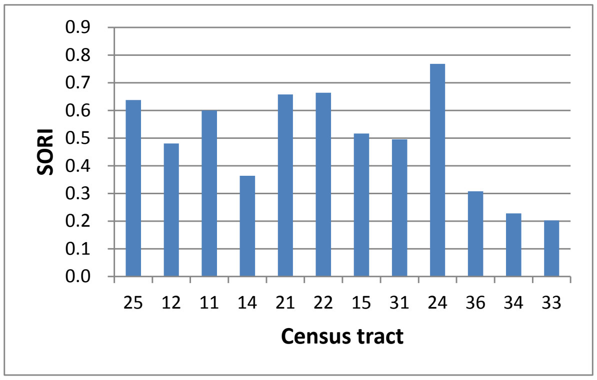

Fig. 3.17. Social Resilience Index (SORI)

Table 3.1. Decision hierarchy model for social resilience

Criteria	Weight	Criteria	Weight
Age	0.265	< 16	0.115
		17-65	0.612
		> 66	0.273
Gender	0.103	Male	0.60
		Female	0.40
Education	0.113	Higher	1.0
Income	0.251	Highest	0.498
		2nd	0.222
		Middle	0.135
		4th	0.092
		Lowest	0.053
Tenure	0.097	Owner	1.0
Disability	0.171	Disable	1.0

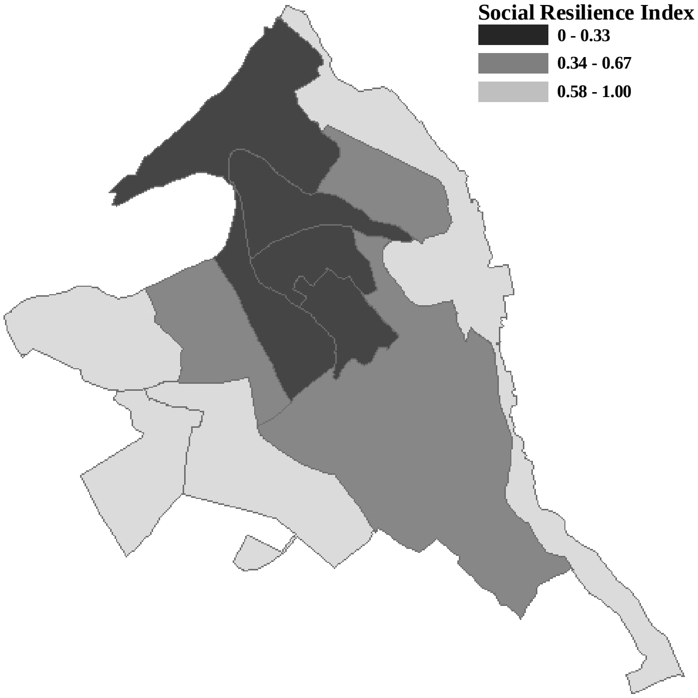

Fig. 3.18. Distribution of Social Resilience Index (SORI)

Hospital/clinic and road networks

As shown in Fig. 3.10, there are 12 medical institutes (red circular mark) in the city, of which nine are clinics, two are regional hospital and only one is national medical center. These medical institutes unevenly distributed in the city. Table 3.2 shows the medical institute density, road density and system resilience index of Tiberias. Tract 11 has the least medical institute density, where 191,753 people share only one hospital. On the other hand, the three clinics and one hospital within tract 14 make the density only 301 people per institutions (Table 3.2). The road density is the ratio of the length of the country's total road network to the country's land area as shown in Table 3.2. Finally, by equally linearly combining the medical institution and road densities for each census tract, we can obtain the system resilience index, as shown in Table 3.2. The top three tracts with the highest SSRI are 21, 14 and 15. Fig. 19 shows how the spatial distribution of SSRI in the city.

Table 3.2. Medical institute density, road density and system resilience index of Tiberias

Tract	Medical institutions density (people/institution)	Road density (km/km^2)	SSRI
24	4,304	10.2	0.25
11	19,753	3.3	0.15
31	6,834	4.6	0.24
25	3,376	9.9	0.32
21	1,024	7.3	0.81
12	3,512	7.0	0.49
22	1,546	9.8	0.66
15	342	0.4	0.68
36	2,584	6.7	0.24
34	3,948	2.7	0.13
14	301	4.2	0.72
33	1,752	2.6	0.22

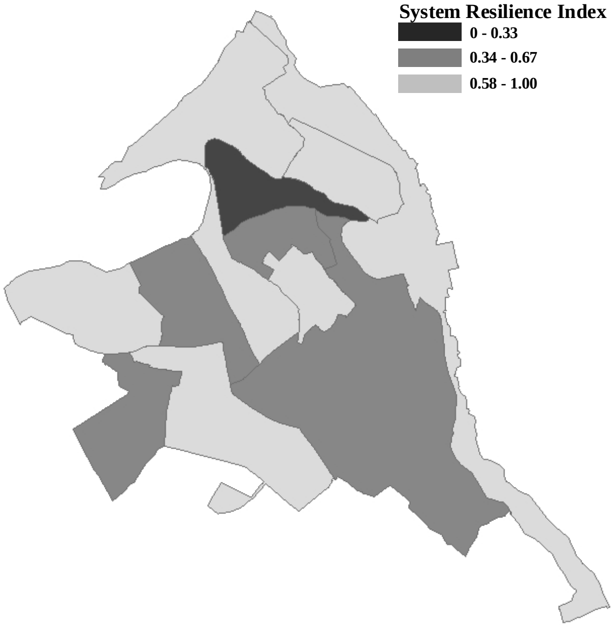

Fig. 3.19. Distribution of System Resilience Index (SSRI)

3.5.2 Assessment of Physical Impacts (Building Damage and Fatalities)

The calculation of building physical impacts and fatalities can be referred to subsection 2.4.2. Here this dissertation uses Jordan 6.0 scenario and the results of building damage (with extensive and complete levels) are shown in Table 3.3 and the results of fatalities are shown in Table 3.4. From Table 3.3, we find that census tract 24 has the highest percentage of building damage – 31.2% of buildings is expected to subject extensive or complete damage. Table 3.4 indicates that census tract 14 has highest percentage of fatalities.

Table 3.3. Building damage

Tract	No. buildings	No. damaged buildings	% of damaged buildings
25	422	47	11.2
12	563	46	8.1
11	357	43	12.0
14	427	55	12.9
21	326	38	11.5
22	276	31	11.2
15	356	62	17.5
31	546	26	4.7
24	122	38	31.2
36	529	33	6.3
34	277	2	0.8
33	274	2	0.8

Table 3.4. Fatalities

Tract	Population	No. Fatalities	% of Fatalities
25	3,038	9	0.3
12	7,023	19	0.3
11	5,926	9	0.1
14	1,205	30	2.5
21	5,122	7	0.1
22	4,638	6	0.1
15	1,198	24	2.0
31	5,467	13	0.2
24	2,152	8	0.4
36	2,584	13	0.5
34	1,974	4	0.2
33	1,752	4	0.3

3.5.3 Assessment of Risk Concentration

In this subsection, the output of the physical impacts including building damage and fatalities from the Jordan 6.0 earthquake scenario is used with the SORI and SSRI to construct a regional risk concentration curves in Tiberias.

Building physical impacts v.s. Social Resilience Index (SORI)

As shown in Table 3.5, the SORI is divided into quintiles in the first column from the lowest (0~0.02) to th3 highest (0.8~1.0), and the building damage is divided according to the quintiles. The building damage is the results of simulation under the Jordan 6.0 scenario and columns 2 and 3 are the relative percentage and the cumulative percentage of building damage ordered by SORI. Fig. 3.20 is the risk concentration curve based on Table 3.5. The SORI concentration curve plots the cumulative percentage of the building damage along the x-axis against the cumulative percentage of SORI along the y-axis. The 45 degree line from the bottom left-hand corner to the top right-hand corner is the equality line. Observing the range of cumulative percentage of SORI from 0 to 0.4, we can find that the concentration curve in this part is below the equality line (with lower slope comparing to the equality line). The results indicate that, surprisingly, the building damage is relatively less among census tracts with lower SORI (0~0.4) comparing to areas with higher SORI. On the other hand, the range of cumulative percentage of SORI from 0.4 to 0.8, we can find that the slopes of the concentration curve in this part is higher the equality line. The results indicate that those census tracts with middle or higher SORI would subject to relatively greater physical impacts comparing to the areas with lower SORI. Finally, also from same curve, we find that the curve between 0.8 and 1.0 SORI became flattened, which means the tracts with highest SORI would subject to relative lower building damage. These findings can also be seen in Fig. 3.21, where shows the spatial distribution of interaction between the building damage and the SORI.

Overall, the findings suggest that the lower social resilient households are less vulnerable to building damage. For instance, tracts 14, 33 and 34 are the three lowest SORI and also subjected to least building damage (Table 3.3). On the other hand, the middle and high social resilient households are more vulnerable to building damage, such as tracts 11, 21, 22, 25 and 31. Meanwhile, the finding also shows that the most social-resilient population is expected to subject to relatively less risk in terms of building damage, such as tract 24. In Tiberias, the old, traditional houses, occupied by poor people, were mostly constructed of wood, or a combination of wood and masonry. These wooden houses are expected to have quite well seismic performance because of their flexibility. The relative modern houses, mostly occupied by middle class, were often constructed of masonry, which is considered to be vulnerable to earthquakes. Despite wood and masonry buildings, the most wealth people often live in those new buildings contracted of reinforced concrete following the least Israeli building code.

Table 3.5. Social resilience index and building damage

SORI	Relative % of bld damage	Cumulative % of bld damage
Lowest	14	14
2nd	8	22
Middle	32	54
4th	37	91
Highest	9	100

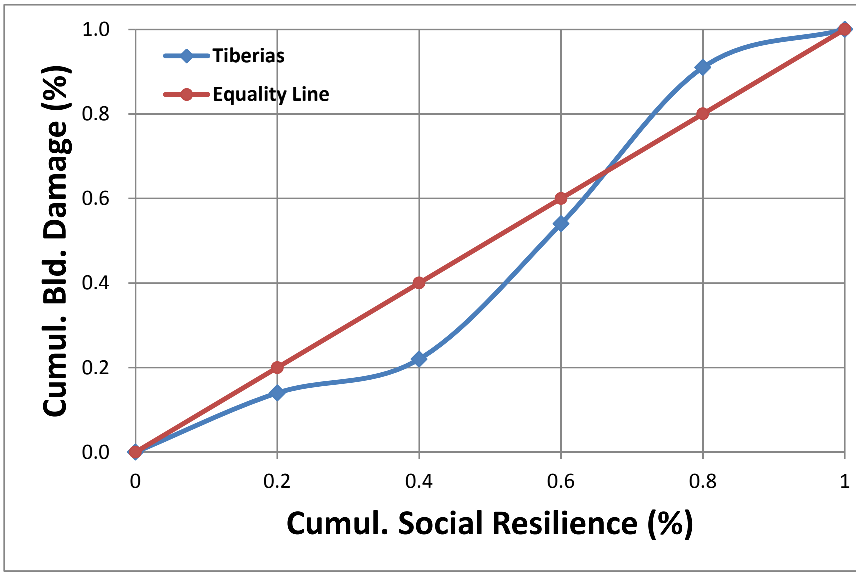

Fig. 3.20. Concentration curve of cumulative building damage percentage by percentage of SORI

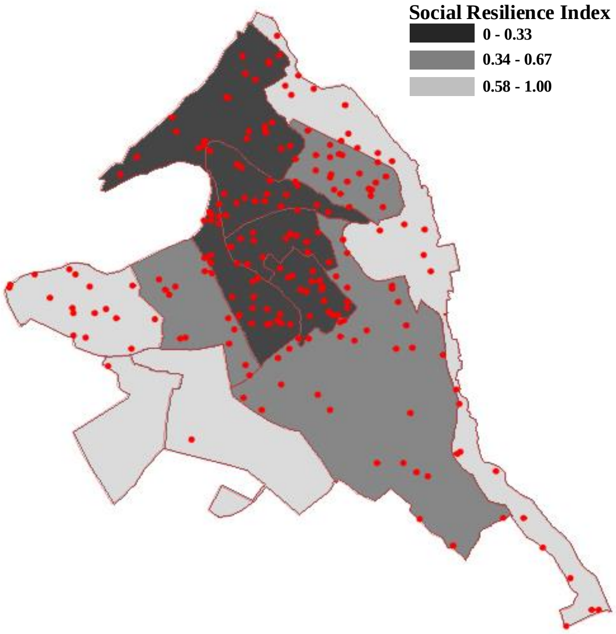

Fig. 3.21. Distribution of building damage and SSRI in Tiberias

Fatalities v.s. System Resilience Index (SSRI)

As shown in Table 3.6, the SSRI is divided into quintiles in the first column from the lowest (0~0.02) to th3 highest (0.8~1.0), and the number of fatalities is divided according to the quintiles. The number of fatalities is the results of simulation under the Jordan 6.0 scenario and columns 2 and 3 are the relative percentage and the cumulative percentage of number of fatalities ordered by SSRI. Fig. 3.22 is the risk concentration curve based on Table 3.6. The SSRI concentration curve plots the cumulative percentage of the number of fatalities along the x-axis against the cumulative percentage of SSRI along the y-axis. Observing the range of cumulative percentage of SORI from 0 to 0.2, we can find that the concentration curve in this part is above the equality line (with higher slope comparing to the equality line). The results indicate that, the number of fatalities is relatively greater among census tracts with lowest SSRI (0~0.2) comparing to areas with higher SSRI. On the other hand, we can find that the slopes of the concentration curve in the 2nd quartile cumulative SSRI is higher the equality line. The results indicate that those census tracts with 2nd quartile SSRI would subject to relatively less fatalities. From same curve, we also find that the curve between 0.4 and 0.8 SSRI became sharp, which means the tracts with higher SSRI would subject to relative greater fatalities. Finally, we find that the curve between 0.8 and 1.0 SSRI became flattened, which means the tracts with highest SORI would subject to relative lower fatalities. These findings can also be seen in Fig. 3.23, where shows the spatial distribution of interaction between the fatalities and the SSRI.

Overall, the findings suggest that the lower system resilient households are more vulnerable to fatalities loss. For instance, tracts 11, 24, 31, 33 34, and 36 are the areas with the lowest SSRI and also subjected to quite serious fatalities responsible for 35.3% of the total fatalities in the city (Table 3.6). Similar, the 4th quartile system resilient households are also vulnerable to fatalities, including tracts 14 and 15. The finding also shows that the most system-resilient population is expected to subject to relatively less risk in terms of fatalities, such as tract 21. In Tiberias, the medical institutions are distributed largely unevenly – five of twelve are located within census tract 14. However, the tract with most population, tract 12, has only two small clinics. Also , the most fatalities are concentrated in the areas with low SSRI. As a result, more emergency medical resources should especially be placed in those low SSRI areas since they would subject to relatively serious fatalities losses.

Table 3.6. System resilience index and fatalities

SSRI	Relative % of fatalities	Cumulative % of fatalities
Lowest	35	35
2nd	6	41
Middle	15	56
4th	39	95
Highest	5	100

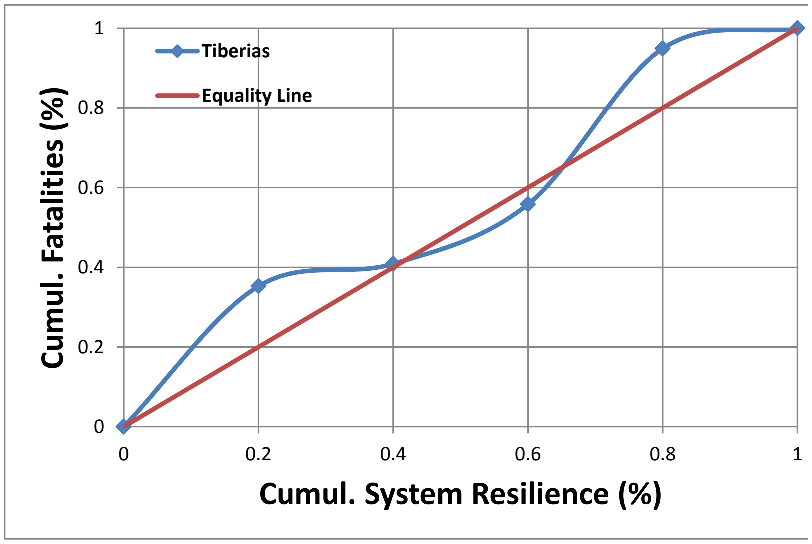

Fig. 3.22. Concentration curve of cumulative fatalities percentage by percentage of SSRI

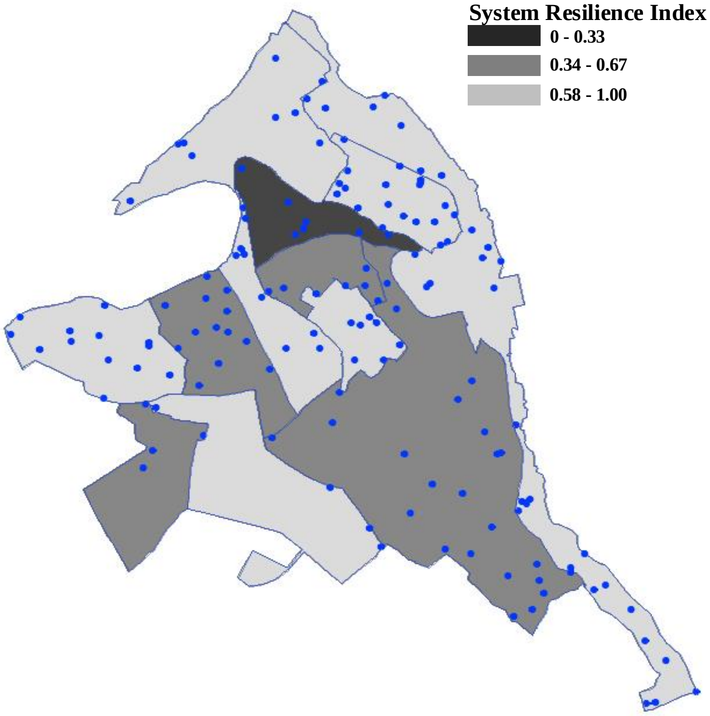

Fig. 3.23. Distribution of fatalities and SSRI in Tiberias

<u>*3.6 Conclusions*</u>

Contributions

This study first thoroughly reviewed both engineering-based and social science-based approaches for assessment of natural hazards risk of urban areas. The natural hazards risk assessments using engineering-based loss estimation modeling usually focus on probabilistic assessment of damage to and losses from the constructed facilities; the social science-based approaches investigate the social and/or system resilience of exposed people and critical infrastructures. A key conclusion that emerged from assessing the existing literature is that these two approaches remain greatly separated and thus they should be integrated to be taken into account interactively. The following key contributions were made to the body of knowledge in the field of natural disaster risk assessment of the built environment:

- Develop a comprehensive framework for assessment of natural disaster risk by integrating physical impacts, system resilience and social resilience of an urban area.
- Introduce a methodology that can identify relatively risky area at community level by means of capturing the interaction between physical impact and socio/system resilience.

The proposed methodology was illustrated by a case study in the city of Tiberias for assessing its seismic risk. The results show that, with regard to the risk associated with the interaction between building damage and social resilience, the lower social resilient households are less vulnerable to building damage in Tiberias due to local characteristics of the distribution of building classification. The result is also shows that, with regard to the risk associated with the interaction between fatalities and system resilience, the lower system resilient households are more vulnerable to fatalities loss. This finding suggests that the medical resources are allocated and transportation access is achieved unevenly by different census tracts in the city. As a result, more emergency medical resources and transport access should be placed in those areas with low system resilience since they are expected to subject to relatively serious fatalities loss.

Limitations and extensions

Followings are some limitations of this study: first, although there are six factors that are included in the calculation of social resilience index, an investigation of more comprehensive factors that influences social resilience can be conducted. For instance, single-parent families, unemployment rate, and ethnicities are all indicated to influence the degree of social resilience. Additionally, the study evaluated system resilience based on the density of medical institutions and roads; however, not only the assessment of the impacts of medical and transport factors can be more advanced by determining the driving time to hospitals, but more critical infrastructures' performance can also be included in the assessment of system resilience. Also, while the proposed methodology has here been applied to the assessment of risks associated with earthquakes, it can be extended to other natural hazards, such as landslide or flooding, for a multi-hazard analysis.

Implications for Practice

This study proposes a metric to serve as a meaningful and operational measurement for the risk reduction decision-making support and help decision-makers select the optimal mitigation solution. Also, this study contributes to the natural hazards management communities' understanding of the integration of physical impact, system and social resilience for identifying risk and the landscape inequality in the capacity of responding to and recovering from the risk.

Chapter 4: Conclusions

Substantial damage to existing buildings and other structures resulting from natural hazards has recently increased due to various factors, such as the climate change and rapid urbanization. The impact of natural hazards on buildings' long-term performance has gained the attention of the building industry as a result of the increasing loss due to hazard events devastating the built environment around the world. As a result, the words "sustainability" and "resilience" are dominating research trends and practical interests in the field of natural disaster management in the built environment. Sustainable development aims to improve the quality of life for present and future generations, in the areas of society, economy, and environment. Resilience represents the conditions of a social system, resulting from physical, social, economic, and environmental factors, in terms of their capacity to cope with, and recover from the impact of hazards.

Sustainability Performance of Constructed Facilities under Natural Hazards

In assessing sustainability performance of buildings in natural hazards, this dissertation made the following key contributions to the body of knowledge in the field of sustainable development of the built environment under natural hazards:

- Developing a comprehensive LCA framework that can incorporate building damage and convert this data into quantifiable environmental impact by means of capturing the main sources of the impact during both pre-seismic structural retrofitting and post-seismic rehabilitation.
- Evaluating the environmental value of hazard mitigation by conducting a risk-

based BCA focused on building lifetime sustainability.

- Introducing a methodology that can translate seismic building damage into clearly quantifiable social, economic and environmental impacts, taking into account the use of various repair methods appropriate to each damage state as well as local economic/environmental data.

The proposed methodology was applied to two alternative retrofit designs with different costs and levels of seismic resistance. The results show that, while neither design could be considered feasible with respect to the three sustainability metrics individually, the lower-cost/lower-resistance design is justifiable if measured by the combined benefit from all three metrics, expressed in monetary terms over a 20-year planning horizon. This finding emphasizes the necessity of a complete sustainable-performance analysis in achieving a cost-effective design. The result is also partially explained by the fact that, based on the findings of our first case study, the prevention of a building from entering a state of complete damage is an effective approach for improving its sustainability performance; and the lower-resistance design is capable of preventing most buildings from being completely damaged, while the higher-resistance one provides only a small additional reduction in the number of completely damaged buildings. Additionally, this dissertation found that when considering all metrics in monetary terms, the cost-effectiveness of retrofitting actions is dominated by social benefits (number of reduced fatalities), followed by reduced repair costs and reduced CO_2 emissions.

Followings are some limitations of this study: first, although the rehabilitation measures for building damage used in our first case study are recommended by

FEMA (FEMA, 2006b), a sensitivity analysis that takes into consideration the variety of repair measures could be conducted to address the uncertainty associated with the proposed method of assessing environmental/economic impacts as a result that various repair measures may exist in practice that correspond to a level of severity of the damage; and the choice of one of these alternatives over another may involve several factors such as time constraints, availability of techniques and resources, and so forth. Additionally, the study evaluated environmental impacts solely based on the activities associated with repair of structural damage; however, the impacts attributable to damage of non-structural components and contents can be included in an extended framework. Also, more research could be done that would allow the environmental/economic benefits of reclaiming materials from demolition to be added to the present LCA framework to achieve a more comprehensive benefit-cost analysis. Meanwhile, other hazard-related recovery activities that have potentially significant environmental impacts should be included in an extended LCA framework. For instance, the extended framework could take into account land-use conversion from previously non-residential areas into residential ones, after disaster-affected areas become uninhabitable: a process that always causes considerable environmental impact in post-earthquake recovery projects (Pan et al., 2014). Finally, while the proposed methodology has here been applied to the assessment of direct losses associated with seismic damage to RC structures, it can be extended to other direct and indirect impacts, such as economic loss of building contents and displaced households considered as social loss, as well as to other building types and/or other hazards.

This study contributes to the building industry’s understanding of the sustainability performance associated with natural disaster risk. Comprehensive assessment, utilizing our proposed methodology, of the effect of hazard-resistant designs on long-term sustainability performance can help decision-makers select the optimal sustainable solution based on designated performance objectives. It is hoped that the present research will serve as a basis for further studies of the long-term sustainability of performance-based designs (new or retrofit) for buildings confronting natural hazards, with the wider aim of achieving optimal cost-effective designs.

Assessment of Risk Concentration of Urban Areas under Natural Hazards

In assessing risk of an urban area subjected to natural hazards, this dissertation made the following key contributions to the body of knowledge:

- Develop a comprehensive framework for assessment of natural disaster risk by integrating physical impacts, system resilience and social resilience of an urban area.
- Introduce a methodology that can identify relatively risky area at community level by means of capturing the interaction between physical impact and socio/system resilience.

The proposed methodology was illustrated by a case study in the city of Tiberias for assessing its seismic risk. The results show that, with regard to the risk associated with the interaction between building damage and social resilience, the lower social resilient households are less vulnerable to building damage in Tiberias due to local characteristics of the distribution of building classification. The result is also shows that, with regard to the risk associated with the interaction between fatalities and system resilience, the lower system resilient households are more vulnerable to fatalities loss. This finding suggests that the medical resources are allocated and transportation access is achieved unevenly by different census tracts in the city. As a result, more emergency medical resources and transport access should be placed in those areas with low system resilience since they are expected to subject to relatively serious fatalities loss.

Followings are some limitations of this study: first, although there are six factors that are included in the calculation of social resilience index, an investigation of more comprehensive factors that influences social resilience can be conducted. For instance, single-parent families, unemployment rate, and ethnicities are all indicated to influence the degree of social resilience. Additionally, the study evaluated system resilience based on the density of medical institutions and roads; however, not only the assessment of the impacts of medical and transport factors can be more advanced by determining the driving time to hospitals, but more critical infrastructures' performance can also be included in the assessment of system resilience. Also, while the proposed methodology has here been applied to the assessment of risks associated with earthquakes, it can be extended to other natural hazards, such as landslide or flooding, for a multi-hazard analysis.

This study proposes a metric to serve as a meaningful and operational measurement for the risk reduction decision-making support and help decision-makers select the optimal mitigation solution. Also, this study contributes to the natural hazards management communities' understanding of the integration of physical impact, system and social resilience for identifying risk and the landscape inequality in the capacity of responding to and recovering from the risk.

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