DISSERTATION

GENERAL EQUILIBRIUM ASSESSMENTS OF A COMPOUD DISASTER AND RECOVERY POLICIES IN NORTHAN TAIWAN

MICHAEL CHUN-YANG HUANG

2015

GRIPS

National Graduate Institute for Policy Studies

GENERAL EQUILIBRIUM ASSESSMENTS OF A COMPOUND DISASTER AND RECOVERY POLICIES IN NORTHERN TAIWAN

A Dissertation
Submitted to the Faculty of the National Graduate Institute for Policy Studies in
Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY IN PUBLIC ECONOMICS

by

Michael Chun-Yang Huang

Main Adviser: Dr. Nobuhiro Hosoe

March 11, 2015

To my beloved mother,

蔡雅蓉 女士

日本と台湾に捧げる

Acknowledgements

I would like to express the deepest appreciation to my main adviser, Professor Nobuhiro Hosoe (細江宣裕) who has the attitude and the substance of a genius: he continually and convincingly conveyed a spirit of adventure in regard to research and scholarship, and an excitement in regard to inspire students with patience. This dissertation would not have been actualized but for his guidance and dedicated instruction. Professor Hosoe has demonstrated a great role model pursuing a wonder of wisdom through economist's instinct, calmness and persistence. I would like to thank my committee members, Professor Tatsuo Oyama and Professor Yuko Akune, whose work directed me transcend academia and practices with a quest for policy-orientation scope.

I appreciate Dr. Minquan Liu and Mr. Atsushi Masuda a lot for their supervision and guide in the Asian Development Bank Institute while I had been granted with an in-depth approach in disaster studies. I thank Prof. Shoichi Ando, Prof. Atsushi Koike, Prof. Hirokazu Tatano, Prof. Tomohiro Kinoshita and Prof. Roberto Leon-Gonzalez for their encouragements and feedback in processing this dissertation. I am more than grateful to Prof. Tetsushi Sonobe for establishing a special development training program that cultivated me with interdisciplinary capacity and global perspectives. In addition, a sincere gratitude to Professor Takashi Fukushima, who introduced me to GRIPS, and whose enthusiasm for enriching "human capital" had lasting effect. I would also like to thank to GRIPS and Interchange Association for their financial support through fellowships.

A great thankfulness should be given to my colleagues for their kindness and generosity sharing me with knowledge and the company most needed: Jerry Xianguo Huang, Yan Zhang, Jing Lan, Ying Yao, Xing Zhang, Chaikal Nuryakin, Rima Prama Artha, Prani Sastiono, Khoirunurrofik, Md. Halley Yudhistira, Mr. Hideo Goto, Ryoko Susukida, Yuki Higuchi, and Kazuya Masuda. As well as the timely Japanese language support from Atsuko Yagi-sensei and Ms. Kasumi Takeuchi.

I must express exceptional thanks to my life mentors, Mr. Soong-Shan Wu (吳松山) and Ms. Su-Tuang Chang (張素瑞) for their warm concerns and enlightenments. My love to my beloved family, who devoted unconditional support during this long journey: my parents – Ya-Jung Tsai (蔡雅蓉) and Jen-Kuo Huang (黃振國); my brother Nightsun Jun-Yen Huang and my dearest better half, Chuyu Yeh (葉楚毓). For these are all the reasons I am with greater responsibility for Japan and Taiwan.

Summary

In recent years, there has been increasing attention and analysis of the tremendous impact of "compound disasters." Compound disasters consist of multiple hazards so that complexity amplifies the damage. The Great East Japan Earthquake (GEJE) in 2011 is the most recent example of a compound disaster; it was triggered by an earthquake, tsunami, and nuclear disaster. In 1999, an earthquake of local magnitude (ML) 7.3 hit central Taiwan. Known as the 921 Earthquake, it was a similar type of compound disaster to the GEJE as it was triggered by an earthquake and electricity shortage. Because Taiwan is ranked as having the highest exposure to multiple natural hazards, with all four of its nuclear power plants built on risk areas, more comprehensive disaster risk management plans are needed. The GEJE highlighted the risk of nuclear disaster in Taiwan and implied the need for a comprehensive analysis of a compound disaster.

This dissertation undertakes a review of the existing literature on compound disasters and finds there is a need to develop a framework to analyze economically the urgent impact of a compound disaster on key industries, wherein their recovery process is described and the effectiveness of policy intervention is examined. The framework can be used to demonstrate the usefulness of simulation studies for disaster risk management as follows.

In the first simulation study, we develop a framework to examine the impact of a short-run disaster on major industries. We use a static single-country computable general equilibrium (CGE) model to simulate a compound disaster involving an earthquake and a power crisis. To estimate the earthquake impacts, we use building collapse rates estimated by the Taiwan Earthquake Estimate Loss System (TELES); and for the power crisis, we assume that all the nuclear power plants are shut down while the power supply gap is substituted by other power generation sources, namely, coal, natural gas, petroleum, and town gas. The simulation results show that Taiwan's major industries, like the semiconductor sector, have high capital intensity and, thus, would be damaged severely in an earthquake. In a power crisis scenario, power prices would rise by 27% and output prices would rise by around 1–2% in each sector. In terms of social welfare, the compound disaster would incur costs of

75,590 TWD per household and add 17% to the damage costs of a single disaster case with only the earthquake.

In the second simulation study, we investigate the impacts of the compound disaster and effects of recovery policies in the long run. We develop and use a dynamic model to describe the recovery process over 30 years. We examine policy interventions in Taiwan's major industries with variations of the recovery program duration and type of subsidy. The simulation results show whether one major sector could achieve sustainable recovery and the extent of fiscal and social costs that would be needed. We examine the effects of production and capital-use subsidies for recovery of the semiconductor, electronic equipment, chemical, and electric power sectors 10 years after the compound disaster, with the subsidies provided for 3, 5, or 7 years. By comparing their fiscal and social costs, it is found that a capital-use subsidy would be more cost effective than a production subsidy. We find that for the semiconductor sector, the annual costs of the recovery program are comparable to 30% of Taiwan's government expenditure. The chemical sector, however, could not achieve any sustainable recovery owing to its heavy dependence on petroleum inputs, which are used more heavily to make up for nuclear power losses. In addition, economy would bear an additional 7% of social losses for the recovery of the semiconductor sector, which equates to 37,411 TWD per household or 3.4% of household income.

Compared with conventional disaster studies from engineering viewpoints of physical losses, the framework developed in this dissertation uses CGE models to focus on quantitative analysis of economic impacts in Taiwan's key sectors and the recovery process under policy interventions. This framework can assist policymakers to manage disaster risks better and develop firm recovery plans based on the results of quantitative assessments. For policy implications, it is suggested that while this framework should be developed regularly and systematically and be used as part of government operations for disaster risk management, more types of disaster databases and micro-level surveys should be conducted in order to enlarge the scope of the framework and improve its accuracy and usefulness. Finally, research limitations of model scope are specified while an annex shows the whole model system developed in this dissertation.

Table of Contents

List of Tables

List of Figures

CHAPTER 1

Introduction

1.1 Natural Hazard, Disaster, and Compound Disaster

The East Asia–Pacific region is the most disaster-stricken region in the world owing to its geology and fast-growing urbanization; it suffers from both small recurrent events and rare high-impact events (ADB, 2013; Davis, 2014). Both developing and developed countries of the region are extremely exposed to natural hazards. Since 1980, 7 of the 10 disasters with the highest deaths in the world occurred in this region, incurring annual economic losses of 60 billion USD (Davis, 2014). From 2010 to 2013, the annual disaster losses from natural hazards amounted to 213 billion USD, which is more than triple the losses of the past 20 years. This is because of the Great East Japan Earthquake (GEJE) in 2011, which caused 15,790 deaths, 210 billion USD of losses (EM-DAT)[1], and disruption of the regional production network. The GEJE not only disrupted production directly in the massive area destroyed by the tsunami (Kajitani, Chang, and Tatano, 2013; Kajitani and Tatano, 2014), but also had an indirect impact owing to disruptions to electricity supply after the nuclear disasters. For example, Japan's current account has been affected significantly owing to the import of energy sources, such as petroleum and liquefied natural gas (e.g., Vivoda, 2014a, 2014b).

The GEJE was a devastating catastrophe because the natural hazards resulted in a series of disasters that not only destroyed buildings and towns but generated fears of radiation effects and power shortages due to a nuclear power disaster. Such disasters caused by multiple natural hazards (e.g., earthquake and tsunami) are regarded as a "compound disaster" (Eisner, 2014). Disasters cannot be understood properly or prevented thoroughly without paying attention to the critical role of human agency and societal processes (Eiser et al., 2012). The severity caused by a compound disaster may be complex, especially when its subeffects overtake the initial event. This is interpreted as a compound disaster, which consists of multiple sequential disaster events that produce "more serious damage than individual disasters occurring independently."

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[1] The International Disaster Database (http://www.emdat.be/database)

Kawata (2011) interpreted a compound disaster by a high number of casualties, a large size of the damaged area, and multiple spawned secondary disasters. When the initial disaster event is not handled properly, the subsequent disasters may even cause more death and economic loss. The 2011 GEJE was a disaster that included an earthquake, tsunami, nuclear power plant accident, power supply failure, and large-scale disruption of supply chains. A similar case occurred in 1999 in Taiwan, where major economic loss was brought about by weak power supply in the aftermath of the earthquake. The Taiwanese case is discussed as follows.

1.2 Taiwan's Vulnerability to Compound Disaster

Taiwan, located in the Asia–Pacific rim of active geological movement, is especially under threat from multiple hazards, such as tropical cyclones, landslides, and mudflow. According to a hazard exposure ranking by the World Bank (Table 1.2.1), more than 40% of the population in Asia and the Pacific are prone to two or more natural hazards, while Taiwan heads the list with 73% of both its population and area exposed to more than three natural hazards (World Bank, 2005). With regard to area of damage and secondary disasters to both land and population, Taiwan also ranks first in the world.

Table 1.2.1: *World's Top 10 Countries Exposed to More Than Three Hazards (%)*

Country	**Total Area at Risk**	**Population in Areas at Risk**
Taiwan	73.1	73.1
Costa Rica	36.8	41.1
Vanuatu	28.8	20.5
Philippines	22.3	36.4
Guatemala	21.3	40.8
Ecuador	13.9	23.9
Chile	12.9	54.0
Japan	10.5	15.3
Vietnam	8.2	5.1
Solomon Islands	7.0	4.9

Source: Natural Disaster Hotspots: A Global Risk Analysis (World Bank, 2005)

Thanks to advanced technology in meteorology, these climatic hazards can be foreseen and many preventive countermeasures can be undertaken ex ante for disaster preparedness and to reduce damage. The exception is earthquakes, which can catch countries off guard, despite the existence of some geological archives. The impact of earthquakes could be amplified owing to urbanization and other natural or man-made hazards, even with advanced early warning systems or strong buildings. Thus, greater disaster impact may be triggered by other hazards, such as tsunamis or, in the case of the GEJE, nuclear disaster. Earthquakes are one of the deadliest natural hazards and they may cause catastrophic losses. In addition, with the development of sophisticated global production networks, the massive damage from earthquakes could result in disruption of supply chains. According to the EM-DAT (Table 1.2.2), even some earthquakes with limited casualties eventually resulted in massive economic losses, such as in the US (1994), Japan (2004), New Zealand (2011), and Italy. For these reasons, the study focuses on compound disaster triggered by an earthquake.

Table 1.2.2: *Estimated Damage from Top 10 Earthquakes*

Rank	Date	Country	Location	Deaths	Estimated Damage (billion USD)
1	11/03/2011	Japan	Northeast Japan	19,846	210.0
2	17/01/1995	Japan	Kobe, Osaka	5,297	100.0
3	12/05/2008	China	Sichuan	87,476	85.0
4	27/02/2010	Chile	Concepcion	562	30.0
5	17/01/1994	US	Los Angeles	60	30.0
6	23/10/2004	Japan	Niigata	40	28.0
7	17/08/1999	Turkey	Izmit, Kocaeli	17,127	20.0
8	20/05/2012	Italy	Finale Emilia	7	15.8
9	22/02/2011	New Zealand	Christchurch	181	15.0
10	21/09/1999	Taiwan	Central Taiwan	2,264	14.1

Source: EM-DAT (http://www.emdat.be/search-details-disaster-list)

However, disaster studies related to Taiwan are rather scarce, despite Taiwan's important role in economic activities and global production networks. Taiwan, an island country with an external trade volume of more than 120% of gross domestic product (GDP), plays an important role in global production networks in information and communication technology (ICT) products, semiconductors, electronic appliances, machinery, and automobile parts based on very rapid and high-level capital accumulation (Chen, 2002; Chiu, 2013). A single company, TSMC, controlled 84% of the most advanced foundry market in 2014 (IC Insights, 2014). As for information products and parts manufacturing, Taiwan is ranked top in the global market for semiconductors, integrated circuit design, and light-emitting diode (LED) components (SEMI, 2013).

Table 1.2.3: *Average Ranking of Countries Prone to Earthquake Disasters*

Rank	Country	Deaths	Total Affected	Estimated Damage (million USD)	Damage per Capita* (thousand USD)
1	US	68	60,642	32,743	540
2	Japan	25,466	1,115,260	355,562	319
3	Italy	367	116,615	25,182	216
4	Taiwan	2,273	111,033	15,127	136
5	New Zealand	182	611,235	24,540	40
6	Chile	587	2,803,584	30,255	11
7	Iran	70,803	1,645,783	9,884	6
8	Turkey	19,690	4,294,503	24,510	6
9	China	91,790	67,278,773	100,862	1
10	Indonesia	177,146	7,746,204	11,338	1

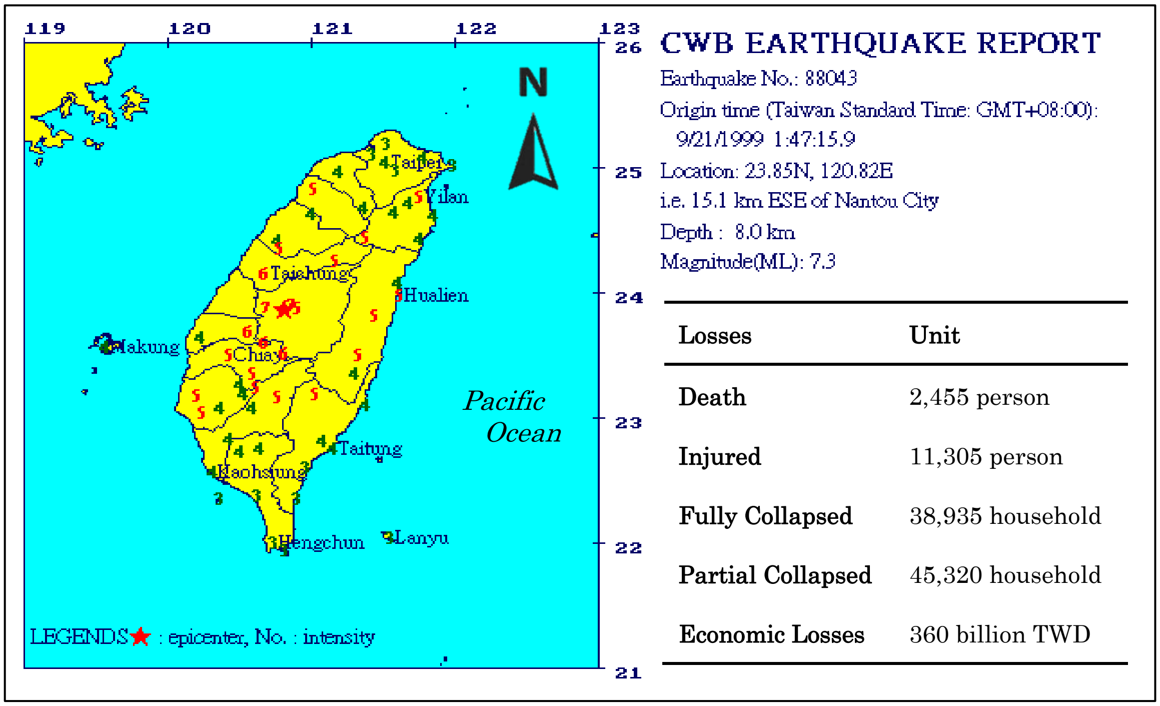
NOTE. Damage per Capita = (Estimated Damage) / (Total Affected), calculated by the author.
Source: EM-DAT (http://www.emdat.be/search-details-disaster-list)

In calculating average damage from earthquakes that occurred in 1990–2013 (Table 1.2.3), it is found that per capita costs in Taiwan are 136,000 USD, which are the fourth highest in the world. Given Taiwan's high-tech export-oriented industries, such as semiconductors and electronic products, its high risk of natural hazards, vulnerability, and exposure place it at great risk of disaster. Because three out of four nuclear power plants are located in at-risk areas close to Taiwan's capital city, Taipei City, with industrial agglomeration, Taiwan faces the threat of a compound disaster in the form of an earthquake and nuclear disaster. Next, Subsection 1.3 reviews the earthquake that occurred in 1999 with a power shortage.

1.3 Compound Disaster in Taiwan

1.3.1 The 921 Earthquake

Compound disaster is no stranger to Taiwan. In 1999, an ML 7.3 earthquake hit central Taiwan (Figure 1.3.1) and badly damaged buildings and major bridges, with many having to be torn down later. The earthquake resulted in a death toll of 2,455 and 11,305 injuries. The direct economic loss was 360 billion TWD, which was equivalent to 4.6% of Taiwan's GDP in 1999. The damage measured as a share of GDP is even higher than that of the GEJE in 2011 (3.6%) and the Kobe earthquake in 1995 (1.9%), implying that smaller island economies are more vulnerable to natural hazards (Executive Yuan, 2006; EM-DAT).



CWB EARTHQUAKE REPORT

Earthquake No.: 88043

Origin time (Taiwan Standard Time: GMT+08:00):
9/21/1999 1:47:15.9

Location: 23.85N, 120.82E
i.e. 15.1 km ESE of Nantou City

Depth : 8.0 km

Magnitude(ML): 7.3

Losses	Unit
Death	2,455 person
Injured	11,305 person
Fully Collapsed	38,935 household
Partial Collapsed	45,320 household
Economic Losses	360 billion TWD

Figure 1.3.1: Earthquake Report and Statistics of the 921 Earthquake

Source: Taiwan Central Weather Bureau, Executive Yuan (2006)

The disaster impact was not limited to life and building losses, but also resulted in supply chain disruption for ICT production. Earthquake shaking not only forced the automatic temporary shutdown of two nuclear power plants in northern Taiwan but also tilted electricity transmission towers, which resulted in a power shortage. The two-week power stoppage hit manufacturers of high-tech semiconductors and RAM in the Hsinchu Science Park hard, even though they were 120 km from the epicenter of the earthquake. At the time in the 1990s, Taiwan accounted for a significant proportion of the world supply of semiconductors and RAM. Thus, production stoppages at the Hsinchu Science Park and other factories caused computer memory prices to triple on world markets. This was, in fact, the first time that global ICT supply chains were affected by a disaster. In the semiconductor manufacturing sector alone, the estimated losses were reported as 11.8 billion TWD, which reduced annual GDP by 0.05%. In addition to this loss, it was estimated a 43.6 billion TWD decrease in annual GDP, while the indirect losses were estimated to reach 1 trillion TWD, and including the costs of the expected disaster recovery policy, the deficit was expected to surge to 180 billion USD (Executive Yuan, 2006).

Immediately after the earthquake, Mai et al. (1999) conducted a loss estimation and showed a 47.4 billion TWD decrease in consumption in the year after the earthquake, equivalent to −0.24% of annual GDP. Other losses from the two-week blackout were 50 billion USD and, thus, the total manufacturing sector lost nearly 70 billion TWD, equivalent to 1% of sectoral output. Furthermore, the earthquake impact reduced exports by 0.67% and imports by 0.035%. In addition, the DGBAS estimated a 43.6 billion TWD decrease in annual GDP and indirect losses of 1,000 billion TWD (Executive Yuan, 2005). Moreover, along with the expected disaster recovery policy, the deficit surged to 180 billion TWD. The main disaster impact of the 921 Earthquake in Taiwan was caused by a natural hazard and electricity shortage. This case clearly shows that the indirect impact caused by compound disaster may be more pervasive than the direct damage on buildings and infrastructure.

1.3.2 Taiwan's Recovery Policy for the 921 Earthquake

The recovery policy for Taiwan's 921 Earthquake made provision for a 3-year special recovery budget of 212.4 TWD billion for 1999–2001 although the recovery work actually continued until 2006. As the earthquake occurred in central Taiwan, which has no primary industrial areas, the special recovery budget was used mainly for infrastructure and housing reconstruction. In addition, the Central Bank made available 100 billion TWD for housing reconstruction and an additional 110 billion TWD in loans to small and medium enterprises (SMEs). However, the approved loan applications amounted to only 25% of the 110 billion TWD available; this considerably low rate implies that targeting appropriate sectors should improve the effectiveness of the recovery policy.

The primary losses in the 921 Earthquake were residential houses (for a detailed discussion, see Shieh, 2004). The earthquake-affected area comprised mainly sightseeing spots, and thus, many tourist facilities were severely damaged. According to the earthquake review report, more than 47 billion TWD or more than 20% of the overall recovery budget went to tourism promotion and community reconstruction. Thus, in the recovery policy literature to date, the primary focus has been the stimulus plan and economic development of the tourism sector (e.g., Tsai and Chen, 2011; Huang and Min, 2002; Kim, Chen, and Jang, 2006; Lee and Chien, 2008).

1.3.3 Nuclear Disaster and Energy Concerns

Taiwan's development and economic growth contributed to the increase of energy capacity after the 1970s (Fukushige and Yamawaki, 2015). Nuclear power plants played an important role in power supply. After the nuclear disaster in Fukushima, Taiwan's concerns about the threat from nuclear disaster rose and losses from possible nuclear disaster have been illustrated since then (Chan and Chen, 2011). Despite these concerns, the disaster risks have not been examined sufficiently. Rodríguez-Vidal, Rodríguez-Llanes, and Guha-Sapir (2012) indicated that among world's 23 nuclear reactors built in at-risk areas, 6 are in Taiwan and 2 are still under construction. These commercial nuclear plants are highly exposed to the threat of earthquakes and tsunamis. Moreover, Taiwan's six nuclear reactors are within 50 km of the capital city. If a major earthquake occurred in this area, the region would suffer not only direct damage, such as loss of human lives, building collapse, transportation disruptions, but also a power crisis owing to the shutdown of the nuclear power plants. This could critically affect industrial production, economic development, and worsen the trade balance and consumption of household energy goods (Itakura, 2012; Vivoda, 2014a, 2014b). Such a threat and its impact on Taiwan's most important metropolis is now one of the largest concerns to be tackled by the government.

1.4 Objectives

The objective of this dissertation is to develop a practical framework of disaster policy analysis for Taiwan's macro economy. More specifically, the dissertation aims to develop a method to estimate losses in capital and labor force availability based on existing disaster shock estimates and assessments, which usually are made from an engineering viewpoint. Furthermore, the dissertation develops a method to construct a comprehensive macroeconomic model for disaster impact analysis, wherein various disaster shocks are simulated and their economic impacts are quantified. Finally, this model is applied to examine the effects of recovery policies in response to a compound disaster.

To demonstrate the usefulness of the recovery framework, a computable general equilibrium (CGE) model is constructed and applied to Taiwan using a hypothetical earthquake and nuclear power shutdown in northern Taiwan. The model quantifies the economic consequences of the compound disaster and examines possible policy options for the recovery of some key industries, such as the semiconductor and chemical sectors. The effectiveness and duration of the recovery program is evaluated in the framework. The dissertation is expected to provide disaster risk management policymakers with an empirical and scientific framework that is useful for developing and examining policy options for better preparedness and recovery against a compound disaster.

1.5 Dissertation Structure

The rest of the dissertation is organized as follows. Chapter 2 discusses compound disaster using existing literature and cases. Quantitative disaster assessment methodologies are introduced while the analysis constraints of the current disaster impact estimate system are reviewed. This chapter states the prerequisite of developing a comprehensive framework of macroeconomic scope in order to clarify the implications of disaster impact for key industries and the recovery process under policy intervention.

Chapter 3 develops a static, single-country CGE model to analyze the economic impact on key sectors of a compound disaster in Taiwan. The chapter considers the individual disaster components of labor loss, capital loss, and power crisis, and finally, combines them to simulate a compound disaster comprehensively. The simulation results show the disaster impacts on many aspects of sectoral output, output price, external trade, as well as welfare analysis.

Chapter 4 investigates the long-run impact of a compound disaster in northern Taiwan with a dynamic CGE model, which is an extension of the static model in Chapter 3. After simulating losses in capital and labor with a nuclear power shutdown, policy experiments are conducted aimed at the recovery of Taiwan's major industries by subsidizing their output or investment. Different types of recovery policies are implemented with welfare analyses to examine their cost effectiveness and appropriate duration.

Chapter 5 wraps up the dissertation by summarizing the empirical simulation experiments in Chapters 3 and 4. In addition, this chapter provides comprehensive concluding remarks with policy implications. The annex shows the whole model system that is developed in this dissertation.

CHAPTER 2

Literature Review

2.1 From Disaster to Compound Disaster

"Disaster," defined as a serious disruption with losses that exceed the capability of a community or society (UNISDR, 2009). In recent years, greater disaster impacts have been caused by natural hazards, both intersectorally and intercontinentally, owing to more complex urbanization and interconnection among various industries (Davis, 2014). However, the occurrence of catastrophic disaster with other sequentially occurring natural hazards or man-made disasters has not yet been specified. Bissell (2013) referred to such a disaster that occurred successively and in combination as a hypercomplex disaster. McEntire (2006) specified that a complex disaster is caused by a natural hazard involving multiple variables. Kawata (2011) highlighted the compounding feature of disasters, pointing out that such catastrophic disasters tended to be caused by multiple disaster events and to be "superwide" in areas of damage, with prolonged recovery periods owing to their massive scale. Eisner (2014) stated that such multiple, independent, sequential, or simultaneous events involved progressive failures of infrastructure, resulting in catastrophic infrastructure collapses or disruption of transportation or energy networks.

"Compound disaster" is a new term in disaster studies because of its complexity, and thus, is analyzed properly from an interdisciplinary perspective only rarely. We mainly use the term compound disaster" in this dissertation in its straightforward meaning. The Great East Japan Earthquake (GEJE) in 2011 could be regarded as the most recent case of a compound disaster, starting with an earthquake that triggered a tsunami and nuclear disaster. The two natural hazards, that is, the earthquake and tsunami, devastated the coastal area of Japan, including great physical damage to six nuclear power plants. The inoperability of many factories manufacturing automobile and electronic parts in the affected area has disrupted global supply chains, resulting in massive economic impact (e.g., Park, Hong, and Roh, 2013).

2.2 Conceptualized Compound Disaster

Every disaster contains compound elements of its process so that severity is amplified to a catastrophic impact. Kawata (2011) identified that catastrophic disasters may contain extensive, prolonged, and compound features. The “extensive” feature has a geographic connection; the “prolonged” feature refers to the capacity to cope with the disaster; while the “compound” feature refers to the extra punch of cumulative natural hazards that cause more serious damage together than individual disasters. While a disaster occurs independently, other subsequent “small” disasters are called “secondary” disasters. Perrow (1999) argued that the nuclear disaster in the GEJE is highly coupled with and constrained by natural hazards and an irresponsive system. These approaches focused on the disaster nature and response process that may have worsened the severity of the disaster. These sequentially occurring disasters may have significantly weakened the disaster response system and resulted in catastrophic losses.

In addition to the GEJE, Eisner (2014) exemplified the compound disaster of the Great Kanto Earthquake (1923) and Haiti Earthquake (2010) by the features of its subevents, such as conflagration and contagious disease. Zobel and Khansa (2014) found interactive impacts though a numerical measure in the presence of multiple related disaster events by considering the tradeoffs between multiple criteria for individual subevents. Kajitani and Tatano (2014) investigated a method to quantify the production capacity loss rate (PCLR) of industrial sectors damaged by various potential disasters. Their estimated PCLR in the manufacturing sectors are comparable to the actual production index.

As the discussion for the mechanism of compound disaster has entered the mainstream of disaster studies, with the specification continuously made for past cases, we apply these cases for researchers and policymakers to analyze collective disaster impacts. For this reason, based on such previous disaster cases as the GEJE and Taiwan’s 921 Earthquake, this dissertation uses multievents features to quantify the impact of a compound disaster that consists of earthquake losses and a power crisis through a general equilibrium approach. The following section reviews the literature on other impact assessment methods.

2.3 Quantitative Approaches to Disaster Impact

2.3.1 Resilience and Macroeconomic Data Approach

In recent years, increased attention has been given to research on static and dynamic approaches using the concept of "resilience" to describe disaster impact and the ability to recover. Rose (2007, 2011) specified that static economic resilience refers to direct losses from a predisaster condition of efficient allocation of existing resources, while dynamic economic resilience indicates the speed of recovery from the capital stock. Kajitani and Tatano (2009) introduced lifeline disruption with quantified impact using survey data of industries in Japan. Some regional impact assessments of transportation losses were conducted for Japan using spatial analysis (e.g., Tsuchiya, Tatano and Okada, 2007; Tatano and Tsuchiya, 2008; Koike, Tavasszy, Sato, and Monma, 2012). However, at the macroeconomic level, there are is significant interdependency among economic variables that influence equilibrium, such as price and quantity. With the development of disaster data archives, there has been growing importance in the last decade on research of disaster impact assessment. Noy (2009) used cross-country data of number of deaths, affected population, and economic losses from EM-DAT and found that developing countries and small economies are more vulnerable and face much larger shocks, both directly and indirectly, than large and developed countries. To measure disaster losses from complex impacts, Input–output (IO) models are employed in many studies to measure and evaluate the economic impacts of disasters under the regional economic structures, specifically, the cascading effects of interdependent failures to estimate economic resilience. Okuyama (2004) investigated the dynamic nature of the impact path over space and time in relation to the Kobe Earthquake. The social accounting matrix model can help to examine higher-order effects across different socioeconomic agents, activities, and factors. Okuyama and Sahin (2009) estimated the global aggregate of disaster impacts during 1960–2007 by analyzing 184 major disasters in terms of the extent of economic damage and found a growing trend of their economic impacts over time.

2.3.2 Computable General Equilibrium Approach

In terms of methodology, the study of economic impacts seems to have moved from cross-country data analysis to economic simulations in order to tackle specific policy implications and quantified impacts. While the computable general equilibrium (CGE) model could be used for assuming the exogenous shocks to an economy as a disaster scenario, this dissertation attempts to contribute to the literature of impact assessments of disaster research. A CGE model is a description of an economy using a system of simultaneous equations while the "general equilibrium" model implies that all markets, sectors, and industries are modeled together with corresponding interlinkages. CGE models describe the whole economy and its transactions between diverse economic agents, such as production sectors, households, and governments (Sue Wing, 2011).

CGE models are capable of analyzing the details of a macro economy driven by a price mechanism using only small data requirements (e.g., a 1-year IO table) and the calibration method (Hosoe, Gasawa, and Hashimoto, 2010). The model can manipulate backward or forward impacts on losses in sectoral capital stock as disaster "shocks." Its economic impacts could thereby be derived from a shock, or the implementation of a specific policy after a disaster could thereby be captured. This approach is adapted to interpret disaster shocks on markets and prices in the short run. For example, Rose and Guha (2004) applied the CGE model to analyze the electric utility lifeline losses from earthquakes. In addition, other CGE models could be applied for lifelines and other hazards. Considering both static and dynamic analyses, Rose and Liao (2005) used a CGE model to analyze the impact of water service disruptions by earthquakes and estimated resilience in various situations. Furthermore, these CGE models are used widely to analyze the aggregate welfare and distributional impacts of policies through multiple markets for various types of tax and subsidy (Adam, 2013).

When formulating disaster recovery policy, the long-run estimation of the recovery process is important for government planning. Akune, Okiyama, and Tokunaga (2013) used a spatial computable general equilibrium (SCGE) model to predict recovery time needed for the fishery and marine products industries using the current recovery grants-in-aid after the GEJE in Japan. Documented costs to date include 2.9 trillion JPY in insurance payouts and 17.7 trillion JPY in response and recovery budgets by the national government, financed largely by household tax increases and bonds (Board of Audit of Japan, 2013). Okiyama, Tokunaga, and Akune (2014) used a dynamic CGE model to simulate the GEJE and studied efficient financing measures of reconstruction funds. Their methodology has shed light on the CGE application of disaster recovery analysis and could be extended with broader policy perspectives with specific simulation. Similarly, Xie, Li, Wu, and Hao (2014) used a dynamic CGE approach in relation to estimation of the Wenchuan Earthquake (2008); three scenarios compared the effectiveness of the reconstruction plan with predisaster conditions. By inserting the actual reconstruction data into the model, they forecast that the reconstruction plan would accelerate the economic recovery as measured by GDP by 4 years. Their quantitative results are very informative for understanding the recovery path and effects of policies for recovery.

2.3.3 Recovery Process Estimation

Given the occurrence of a disaster, we have to describe its recovery process in order to develop and examine its recovery plans. The recovery implies time for the economic system or output level to recover to predisaster conditions (c.f., Henriet, Hallegatte, and Tabourier, 2012; Hallegatte, 2014). In analyzing the relationship between complex industrial sectors for their supply-chain restoration, Nakano and Tatano (2008) developed a two-sector economic growth model and found that the decline of final goods production was not due to physical damage but to the decrease of intermediate goods.

The GEJE provided sharp lessons for manufacturing supply chains. Kajitani, Chang, and Tatano (2013) argued that loss estimates should be larger when we include the impacts of supply-chain disruption, retail trade, and tourism owing to reduced consumption and nuclear disaster concerns. Their study emphasized the linkage between production of intermediate goods and final goods. Although these approaches illustrated the complexity of compound disaster with some implications, they were limited to only a single sector or community scale. To provide practical information for policymakers, it is critically important to undertake quantitative impact assessments with details that can describe the disaster impact at the level of policymakers' interventions.

2.3.4 Loss Estimation in Taiwan

Since 1998, The Taiwan-HAZ system has been developed to promote research on seismic hazard analysis, structural damage assessment, and socioeconomic loss estimation. Many comprehensive hazard maps and hazard analyses can be accessed in the system with instant simulated scenarios. Yeh, Loh, and Tsai (2006) introduced it's the estimation methodology of seismic losses using the Taiwan Earthquake Loss Estimation System (TELES). The loss estimates of buildings and infrastructure, casualties, and mortality can be generated by inserting earthquake locations. Many impact analyses have been conducted based on this system (e.g., Lin et al., 2012; Liu, Tsai, and Chen, 2013). The strength of the system is its analysis of shaking and building damage; however, its economic loss estimates are measured in terms of reconstruction costs rather than industrial activities. In order to quantify sectoral disaster impacts, this dissertation develops a practical method to combine the loss estimate generated by TELES with the geographic concentration of industries.

2.4 Concluding Remarks

Taiwan has high risk of compound disaster while its nuclear power plants are both exposed and vulnerable. Attention on the compound disaster of multiple hazard events has been growing but there is only a little research on their impact analysis and synergic mechanisms. This chapter has reviewed several disaster impact assessments through various approaches with heightened analytical usefulness. The damage resulting from a compound disaster could be devastating, and thus, it is desirable to develop a comprehensive framework of disaster impact assessments to figure out sectoral vulnerability and the recovery process under policy intervention after a potential compound disaster. For this reason, this dissertation applies CGE models to simulate a compound disaster in northern Taiwan. The details are specified in Chapters 3 and 4.

CHAPTER 3

Disaster Impact Assessment

3.1 Introduction

3.1.1 Risks and Concerns of Compound Disaster

East Asia and the Pacific comprise the most frequent disaster-stricken region in the world, suffering from small recurrent events as well as rare high-impact events. Island economies are much more likely to be hit hard by disasters (Narayan, 2003; World Bank, 2010), and thus, resilience is increasingly recognized as an important dimension of the sustainability of disaster risk management (DRM) systems (ADB, 2013). Located in the Asia–Pacific region, Taiwan is especially threatened by multiple hazards because 99% of its land and population are exposed to risks while 73% of the total area and population are at risk of high mortality from more than three hazards (World Bank, 2005). Globally, Taiwan is ranked as the nation most vulnerable to hazards, followed by Costa Rica, Vanuatu, and the Philippines.

Taiwan is a trade-orientated country with an external trade volume of more than 120% of its GDP, and the country plays an important role in global production networks in information and communication technology products, semiconductors, electronic appliances, machinery, and automobile parts based on very rapid and high-level capital accumulation (Chen, 2002; Chiu, 2013), as shown in Table 3.1.1. A disaster could affect not only production but also exports by destroying primary factors and disrupting their supply chains.

Table 3.1.1 *Industry Profiles in Taiwan*

Sector and Abbreviation		**Output Share**	**Electricity Intensity** [c]	**Capital Intensity** [d]	**Armington Elasticity** [e]
Agriculture	AGR	1.5%	0.7%	0.43	2.36
Crude Oil and Natural Gas [a,b]	PAG	2.5%	0.1%	0.50	7.35
Mining	MIN	0.3%	0.4%	0.60	0.90
Coal [a]	COA	0.5%	0.2%	0.47	3.05
Food	FOD	2.2%	1.4%	0.34	2.47
Textiles and apparel	TXA	1.9%	2.9%	0.19	3.78
Wood and paper	WPP	1.2%	2.1%	0.31	3.06
Petroleum [a,b]	PET	3.6%	5.9%	0.31	2.10
Chemical	CHM	9.4%	12.1%	0.47	3.30
Pottery	POT	0.9%	2.3%	0.42	2.90
Steel	STL	4.1%	4.7%	0.59	3.75
Metal products	MET	4.0%	2.8%	0.24	3.43
Semiconductors	SEC	13.3%	8.6%	0.68	4.40
Electronic equipment	EEQ	5.0%	1.9%	0.34	4.40
Machinery	MCH	4.0%	0.8%	0.24	4.05
Transportation equipment	TEQ	2.3%	0.9%	0.25	3.14
Manufacturing	MAN	1.1%	0.7%	0.31	3.75
Electricity [a,b]	ELY	1.4%	10.7%	0.76	2.80
Town gas [a,b]	TWG	0.1%	0.1%	0.51	2.80
Construction	CON	3.5%	0.6%	0.19	1.90
Transportation	TRS	3.1%	1.0%	0.45	1.90
Services	SRV	34.2%	22.6%	0.45	1.91

Notes.

[a] Energy goods used for industrial production.

[b] Energy goods used for household consumption.

[c] Share of electricity input costs of total production costs.

[d] Capital intensity is defined as a portion of remuneration of capital of total sectoral value added.

[e] Armington's (1969) elasticity of substitution, provided in the GTAP Database, version 8.

In addition, the world recently learned lessons from experiences during and after the Great East Japan Earthquake (GEJE) in 2011 about how communities and industrial supply chains were disrupted by an earthquake with a tsunami, nuclear disaster, and power crisis (World Bank & GFDRR, 2012). When the initial disaster event is not handled properly, subsequent disasters could cause a higher death toll and larger economic losses, as was learned from the Fukushima nuclear disaster. This could lead to the occurrence of multiple disasters—a "compound disaster" (Kawata, 2011; Davis, 2014).

Indeed, Taiwan experienced a similar compound disaster triggered by a magnitude 7.3 earthquake on September 21, 1999 (hereinafter, the 921 Earthquake). The estimated economic damage of the earthquake was 14.1 billion TWD, and the disaster ranked 10th in terms of economic loss among worldwide disasters between 1983 and 2013. The Ministry of the Interior reported 2,321 deaths and 82,238 households and buildings that were partially or fully damaged by the debris from collapsed buildings and mountain landslides as a result of the 921 Earthquake.[2] Indirect losses accrued as the damaged facilities ceased operation and production, resulting in the unavailability of various services. For example, the tilt of electricity towers triggered a blackout and power shortages for two weeks and affected the Hsinchu Science Park, known as the silicon valley of Taiwan, in which located in an area 120-km away from the epicenter. This caused the loss of 16.7 billion TWD (538.7 million USD in 1999 value) in semiconductor manufacturing, and furthermore, reduced annual GDP by −0.24% (Mai et al., 1999). The concern about a compound disaster with nuclear power plants in Taiwan was heightened by the GEJE on March 11, 2011. With 18% of its total power supply dependent on nuclear power, Taiwan is the 15th largest nuclear power user in the world (Chan & Chen, 2011) with three of its four nuclear plants built on the coastline within a 30-km radius of the capital city, Taipei, which has 5.5 million inhabitants.

3.1.2 Earlier Studies

DRM studies started just recently, and thus, are rare in relation to Taiwan, despite their importance. Most existing studies on seismic disasters focus on loss of buildings and life, not on loss of economic activities. Moreover, given the economic interlinkages associated with a compound disaster, disaster risk assessments that consider a single disaster do not suffice. Simulations with good details of industrial activities that are potentially vulnerable to major natural disasters can elucidate the impact of a compound disaster and, thus, are indispensable for making a plausible and holistic disaster mitigation plan.

The Taiwan Earthquake Loss Estimation System (TELES) serves as a useful platform to provide information about risks and potential losses from an earthquake (Yeh, Loh, and Tsai, 2006). TELES provides estimates of direct damage in terms of the number of deaths, injured people, and

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[2] 921 Earthquake Knowledge Base Guide: http://921kb.sinica.edu.tw/archive/dgbas/dgbas05.html

collapsed buildings caused by an earthquake with a magnitude and location that the user stipulates. Based on TELES, Lin, Kuo, Shaw, Chang, and Kao (2012) used an input–output (IO) model to estimate the economic impact of two types of earthquakes—one in north Taiwan, the other in northeast Taiwan—and found that the earthquake in north Taiwan would cause more losses. Their results suggested that the government should make it a top priority to encourage manufacturing sectors to implement earthquake mitigation, such as seismic retrofits, or to provide seismic evaluations, which could enable firms to engage in mitigation voluntarily (Rodríguez-Vidal, Rodríguez-Llanes, and Guha-Sapir, 2012). However, these existing studies considered only a single and static disaster event while omitting risks and possible trouble in nuclear power plants.

In Japan, in which huge earthquakes have been anticipated and experienced, researchers have conducted many studies. For example, Tsuchiya, Tatano, and Okada (2007) and Tatano and Tsuchiya (2008) used an SCGE approach to estimate economic losses due to transportation disruption by earthquakes; they found that the indirect losses would be greater than the direct losses. Liang, Tsuchida, Okada, and Wei (2008) used an SCGE model to assess the labor and capital losses from a Nankai region earthquake in Japan and found that labor and capital would have a strong spillover impact on regions other than the earthquake-stricken regions, especially where megalopolis cities are located. As for other SCGE model applications, Koike, Tavasszy, Sato, and Monma (2012) developed a RAEM-Light CGE model to closely analyze smaller-scale regions of municipalities, and then, analyzed the benefits of road networks in the presence of natural disasters.

In the context of the 2011 GEJE, Yamazaki and Takeda (2013) used a static CGE model to evaluate the impact of a nuclear power shutdown in Japan without considering the catastrophe of the earthquake, and their simulation results showed that an immediate nuclear power shutdown in Japan would have a significantly negative impact on the country's economy and would increase carbon dioxide emissions. Hosoe (2014) used a world trade CGE model to investigate the impact of a power crisis on production and cross-border relocation of industries between Japan and China through foreign direct investment and found that domestic industries in Japan that heavily consume electric power would relocate to China.

As for the economic loss assessment of a seismic disaster in Taiwan, Mai et al. (1999) conducted a comprehensive report on Taiwan's devastating earthquake of 1999 and described the direct and indirect losses on major Taiwanese industries, such as semiconductor and electronic equipment manufacturing. However, economic risk assessments on nuclear and power shortages, such as those of Yamazaki and Takeda (2013) and Hosoe (2014), have undertaken analyses for Japan with a CGE model that have never been undertaken for Taiwan.

Given the abovementioned circumstances, which industries would be affected severely by what kind of factors in a major earthquake? If a power crisis were to follow an earthquake, would power supply need to be allocated, especially to key industries, such as semiconductors, to support their production and exports? To answer these questions, this study develops a CGE model and quantifies the economic impact of a compound disaster comprising a huge earthquake causing direct losses of (a) labor force and (b) physical capital, and a subsequent power crisis with (c) a shutdown of nuclear power and substitution with thermal power. Finally, these impacts are considered simultaneously in (d) a simulation of a compound disaster. The simulation results show that Taiwan's major industries of semiconductors, electronic equipment, and steel would be affected negatively by physical losses of capital and labor but not by the power crisis. On the other hand, the textiles and apparel, chemical, and pottery industries would be vulnerable to a power crisis.

This chapter proceeds as follows. In Section 3.2, the model and methodology is introduced alongside the assumptions and scenarios. In Section 3.3, the interpretation of empirical results is provided, and Section 3.4 suggests policy implications with future extensions.

3.2 Methodology

3.2.1 Model Structure

A CGE model is a useful framework to analyze the economic impact of natural hazards and associated policy response at micro and macro levels (Rose and Guha, 2004; Rose 2007). The CGE model is a multimarket simulation model based on the optimization behavior of individual households and firms, and their market competition, following the standard CGE model developed by Hosoe, Gasawa, and Hashimoto (2010). This study extends their model by describing substitution among various energy sources à la Hosoe (2006; see Figure 3.2.1). The analysis using a multisectoral CGE model sheds light on key Taiwanese sectors, such as semiconductors and electronic equipment. The model distinguishes 22 sectors based on Taiwan's 2006 IO table by the DGBAS (2011a).

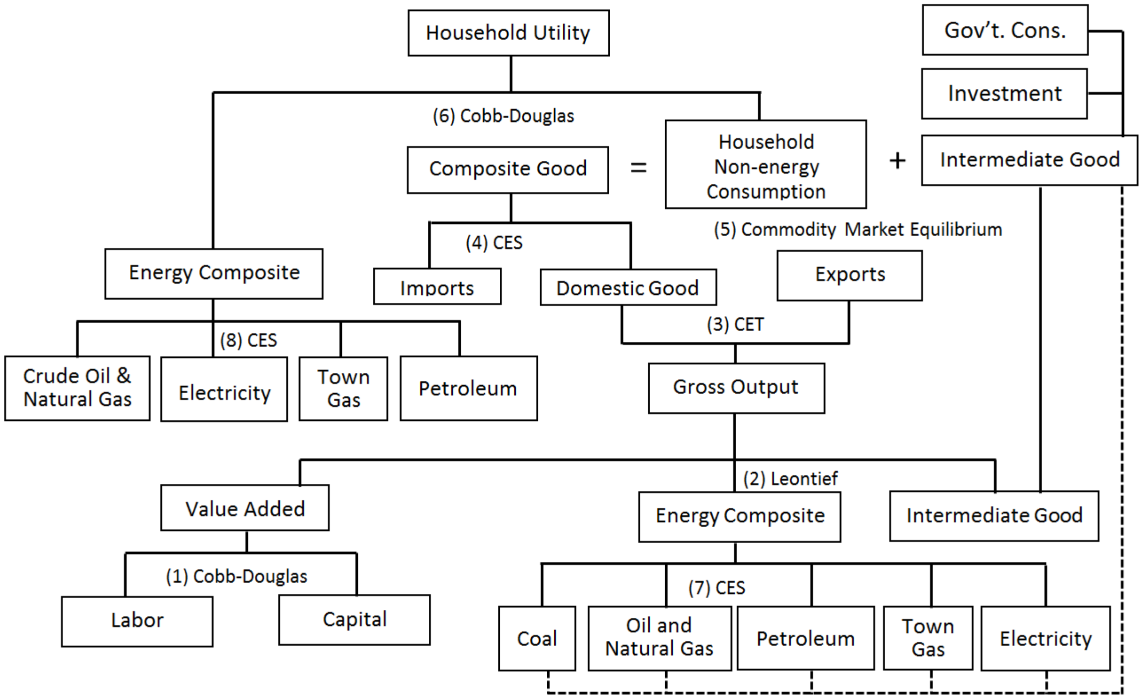

Figure 3.2.1: CGE Model Structure

This model includes the following specifications. First, substitution between capital and labor is assumed in value-added production with a Cobb–Douglas type of production function (parenthetically labeled 1 in Figure 3.2.1). A Leontief-type function (2) is employed for a production function of gross output, which is made up of value added, an intermediate input, and energy composite. Gross output is transformed into domestic goods and exports with a constant elasticity of transformation (CET) function, (3), and a constant elasticity of substitution (CES) function, (4), is assumed for production of composite goods made with domestic goods and imports following Armington (1969). The Armington composite goods (5) are used by a representative household and the government as well as for investment and the intermediate input, while the household utility depends on consumption of various nonenergy goods and an energy composite (6).

Next, the energy composite for nonenergy sectors is made from these four energy goods and coal while we do not assume substitutability among energy sources but conventional fixed coefficient technology for the five energy sectors, (7). Finally, the energy composite (8) for the household comprises petroleum, natural gas, electricity, and town gas (without coal). The model is calibrated to Taiwan's IO table for 2006 (DGBAS, 2011a) using the Armington elasticity of substitution provided by the GTAP Database version 8 (Hertel, 1997) and assuming an elasticity of substitution among energy goods of 1.1.[3]

3.2.2 Compound Disaster Scenario

This study considers a compound disaster as a series of two events, an earthquake and a nuclear power shutdown. The former event would damage the labor force and capital stock directly; the latter would cause a power crisis. To measure the contribution and significance of these impact components in a compound disaster in detail, it is assumed that (a) labor loss, (b) capital stock loss are caused by an earthquake, and (c) the power crisis are caused by the shutdown of nuclear power plants, and then, these three effects are combined in (d) a compound disaster, which is the accumulation of all the abovementioned scenarios.

To set up a hypothetical scenario, the study first assumes the location and magnitude of an earthquake. The study focuses on an earthquake of magnitude 7.5 occurring on the Shan-jiao fault. This fault is known as the most vulnerable fault in terms of shallowness and movement of subterranean magma near Taiwan's capital, Taipei City, and three nearby nuclear power plants (Figure 3.2.2). Feeding these assumptions into TELES/TSSD[4], estimates of the direct damage caused by this assumed earthquake (Table 3.2.1) could be generated.

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[3] The sensitivity tests are conducted with respect to these two elasticity parameters, and little qualitative difference is found in the section of simulation results. Details are shown in Appendix 3.B.

[4] The Internet version of TELES, Taiwan Seismic Scenario Database (TSSD, http://teles.ncree.org.tw/tssd/)

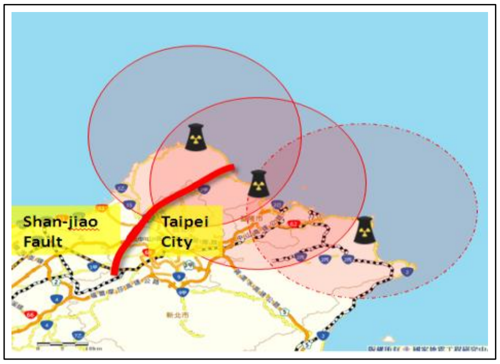

Figure 3.2.2: Assumed Earthquake

Note. The figure shows the geographical locations of the capital city, the Shan-jiao fault (red line) three nuclear power plants (black cooling towers), and a 30-km radius of each nuclear power plant (translucent red ovals).
Source: Adopted from the National Center for Research on Earthquake Engineering, TSSD.

Table 3.2.1: *Assumed Earthquake, Estimated Losses, and Building Collapse Rate (C_r)*

Fault: Shan-jiao (E.121.5074, N.25.1351)

Magnitude: 7.5 /
Length of Fault: 35 km /
Depth of Fault: 5 km /
Estimated Deaths: 10,774 people [a]
Estimated Injured: 14,780 people [a]
Estimated Losses: 1,271 billion TWD

Region	# of Collapsed Buildings	Collapsed Building / Existing Buildings (C_r)
Taipei City	23971	12.6%
New Taipei City	80681	12.4%
Taoyuan County	9073	1.9%
Hsinchu County	88	0.1%
Hsinchu City	96	0.1%
Keelung City	1588	2.2%
Miaoli County	5	0.0%
Iilan County	512	0.4%

Note. [a] The estimated number of deaths, injured people, and losses are not used for simulations; details are discussed below. Data retrieved from the TSSD.

Regarding capital loss estimates, the Taiwan Seismic Scenario Database (TSSD) reports building collapse rates in the r-th region, C_r (Table 2.1). This information is combined with that on the geographic concentration of the i-th industry in the r-th region $X_{i,r}$ and that of population in the r-th region SL_r to estimate the portions of lost capital by sector and lost total labor endowment, respectively (Table 3.2.2). The details of the estimation process of these shocks are shown in Appendix 3.A.

Table 3.2.2: *Estimated Loss of Sectoral Capital Stock and Total Labor Endowment*

Sector		Scenario 1 Labor Loss[a]	Scenario 2 Capital Loss[b]	Scenario 3 Power Crisis	Scenario 4 Compound Disaster
AGR	Agriculture	- -	−1.3%	- -	−1.3%
PAG	Crude Oil and Natural Gas	- -	−4.2%	- -	−4.2%
MIN	Mining	- -	−1.9%	- -	−1.9%
COA	Coal	- -	−5.7%	- -	−5.7%
FOD	Food	- -	−3.9%	- -	−3.9%
TXA	Textiles and apparel	- -	−7.1%	- -	−7.1%
WPP	Wood and paper	- -	−9.6%	- -	−9.6%
PET	Petroleum	- -	−4.9%	- -	−4.9%
CHM	Chemical	- -	−7.4%	- -	−7.4%
POT	Pottery	- -	−6.3%	- -	−6.3%
STL	Steel	- -	−5.8%	- -	−5.8%
MET	Metal products	- -	−6.4%	- -	−6.4%
SEC	Semiconductors	- -	−11.6%	- -	−11.6%
EEQ	Electronic equipment	- -	−11.0%	- -	−11.0%
MCH	Machinery	- -	−6.1%	- -	−6.1%
TEQ	Transportation equipment	- -	−4.1%	- -	−4.1%
MAN	Manufacturing	- -	−5.6%	- -	−5.6%
ELY	Electricity	- -	−3.8%	−12.5%	−16.3%
TWG	Town gas	- -	−5.8%	- -	−5.8%
CON	Construction	- -	−6.8%	- -	−6.8%
TRS	Transportation	- -	−13.5%	- -	−13.5%
SRV	Services	- -	−8.2%	- -	−8.2%
Labor Loss		−7.4%	- -	- -	−7.4%

Note. Calculated and assumed by author. Details of each estimation process are shown in Appendix 3.A.

[a] Labor loss rate $= \sum_{\mathrm{r}} SL_r \times C_r \times 2.$

[b] Capital loss rate $= \sum_r CL_{i,r}$

As shown in Table 2.1, the TSSD provides estimates of the number of dead and injured. However, labor losses could be caused not only by such deaths or injuries but also by unemployment or unavailability due to damaged buildings or commuting trouble. In the end, the number of dead and injured estimated by the TSSD was 0.1% of the population in the affected region, which does not fully reflect the reality of the disaster from the viewpoint of disrupted economic activities. Therefore, in the study, the decrease of labor is estimated on the basis of an *effective* disruption that could be caused by building damage.

The electric power sector was assumed to suffer not only damaged physical capital in the earthquake but also the shutdown of all nuclear power stations triggered by the nuclear disaster or mandated by the regulatory authority for safety reasons. To describe these shocks in the nuclear shutdown scenario, the power sector is assumed to (a) lose 12.5% of its total capital shock, which is comparable to the share in 2012 of nuclear power plants assets of the total assets of the Taiwan Power Company on top of its capital loss from the earthquake. In addition, the power sector is assumed to (b) replace its 18.4% of power generated originally from nuclear power with that from coal, natural gas, and petroleum. The fuel input of the electric power sector is determined by so-called fixed coefficients in the model used in the study. To mimic the interfuel substitution, the input requirement of fossil fuels could be manipulated so that the additional power generation with the fossil fuels could fully cover the lost power from nuclear power generation (Table 3.2.3).

Table 3.2.3: *Nuclear Power Substitution (%)*

Fuel Type	Actual (as of May 2013)			Nuclear Power Shutdown (Power Crisis) Scenario	
	Capacity (MW) / Share (%)	Power generation (MW) / Share (%)	Loading rate (%)	Power generation (MW) / Share (%)	Loading rate (%)
Nuclear	5144 / 12.5	3890 / 18.4	82	0 / 0.0	0
Coal	11297 / 27.5	8580 / 40.6	83	9820 / 46.5	95
Gas	15217 / 37.0	6405 / 30.3	75	8135 / 38.5	95
Oil	3225 / 8.2	676 / 3.2	40	1600 / 7.5	95
Others	6090 / 14.8	8080 / 7.5	85	8080 / 7.5	85
Total	41073 / 100.0	27631 / 100.0	71	27635 / 100.0	81

Note. The Taiwan Power Company is used for the actual case and the author's estimates are used for the hypothetical scenario.

The four scenarios are considered to quantify the impact of these three individual risk factors and their combination (Table 3.2.2). That is, Scenario 1 demonstrates the impact of labor force losses; Scenario 2 demonstrates the impact of the losses of sector-specific capital; Scenario 3 demonstrates the shutdown of all nuclear power plants and the substitution of nuclear power with thermal power. Although these three scenarios would not occur separately in reality, individual examination of each disaster factor helps to investigate their impact on the Taiwanese economy better. Scenario 4 demonstrates the accumulated impact of these three scenarios to depict a compound disaster.

3.3 Simulation Results on Compound Disaster Impacts

3.3.1 Sectoral Impact

In Scenario 1 demonstrating labor losses, all sectors would suffer with some sectoral variations (Figure 3.3.1), partly because labor is mobile among sectors and partly because there are variations of capital/labor intensity by sector (Table 3.1.1). For example, the losses would be the most serious in TXA (−8.5%), EEQ (−5.5%) and MCH(−7.2%), which show high labor intensity. In Scenario 2 demonstrating capital damage, while most sectors would experience output decreases of 1–3%, the largest loss would occur in SEC (−9.9%). This is due to its high capital intensity and geographical concentration in the northern Taiwan region, in which the assumed epicenter is located. Even though all the sectors are assumed to suffer capital losses in the capital loss scenario, such sectors as TXA, MCH, and TEQ would experience gains. They are relatively labor-intensive industries, and thus, could benefit from hiring more workers released by the severely declining sectors.

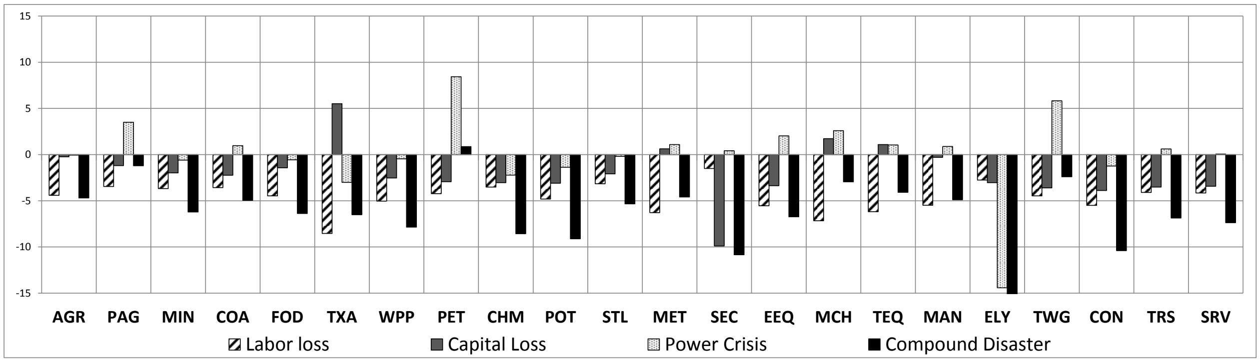

Figure 3.3.1: Impact on Sectoral Output (changes from the base, %).

Note. The output decline in ELY would be −19.8% in the compound disaster scenario.

Scenario 3 shows the impact of the nuclear power shutdown with a subsequent switch to fossil fuels. The output of PAG (3.5%), COA (1.0%), and PET (8.4%) would increase significantly because of their increased demand as substitutes for nuclear power. The output of ELY would drop by 14.4% due to the loss of its nuclear capacity. Power prices would rise to 27% and would be transmitted into price rises in manufacturing products of 1–2% (Figure 3.3.2). Among these manufacturing products, the output of TXA and CHM would decrease by 3.0% and 2.2%, respectively, owing to this sharp increase in power prices. In contrast, the output of EEQ and MCH would increase because they are not as heavily dependent on electric power as an intermediate input in their production processes. SEC would be affected only marginally despite the sharp power price increase.

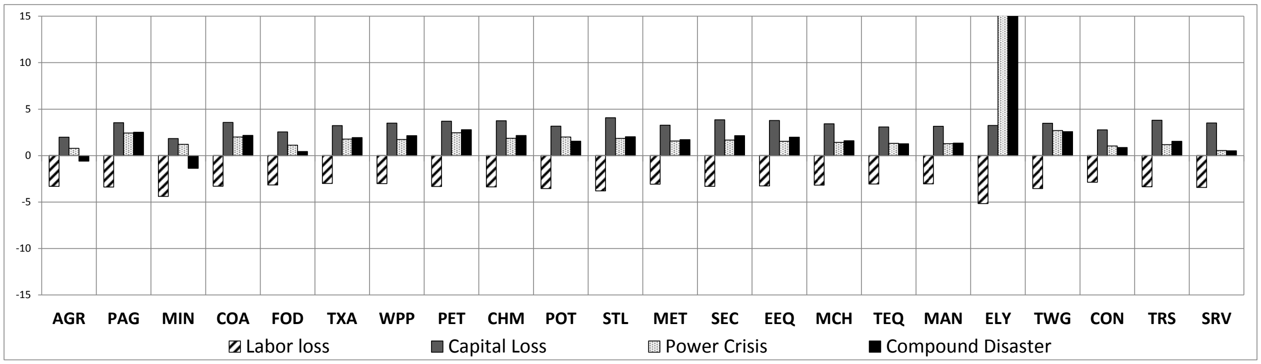

Figure 3.3.2: Impact on Sectoral Output Prices (changes from the base, %).

Note. The price rise in ELY would be 26.7% and 24.9% in the power crisis and the compound disaster scenarios, respectively.

The compound disaster, Scenario 4, assumes all shocks of labor, capital loss, and the power crisis after the seismic disaster. While all the nonenergy sectors would suffer losses of 5% or more, the source of their losses would differ, as shown above. Significant losses would occur in the SEC (−10.8%) and EEQ (−6.7%) industries, as well as CON (−10.4%), POT (−9.1%), and SRV (−7.4%).

In terms of external trade, large increases of imports would occur in such energy sectors as PAG and PET in the power crisis scenario while imports would decrease generally because of the disrupted domestic production and final demand affected by the income loss (Figure 3.3.3). The sectoral exports are affected differently, according to their input intensity of labor, capital, and electricity. Exports would decrease in such sectors as TXA (−9.6%), MET (−7%), MCH (−7.6%), TEQ (−6.9%), and MAN (−6.4%) mainly owing to labor losses (Figure 3.3.4). Each of these changes matches those of the sector's domestic output.[5]

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[5] A large change of electricity exports and imports is shown in Figures 3.3.3 and 3.3.4. These relate to consumption of electricity by foreigners and by Taiwanese abroad and are negligibly small. Therefore, these results have little significance in the analysis.

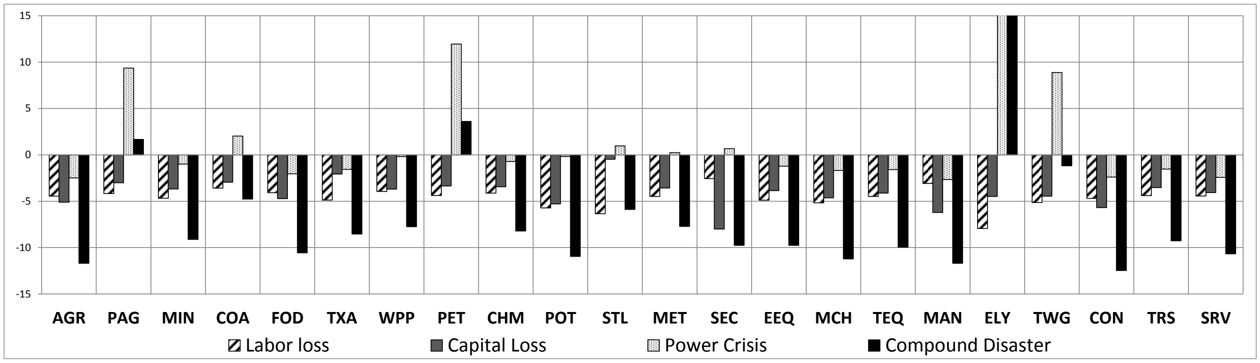

Figure 3.3.3: Impact on Sectoral Imports (changes from the base, %).

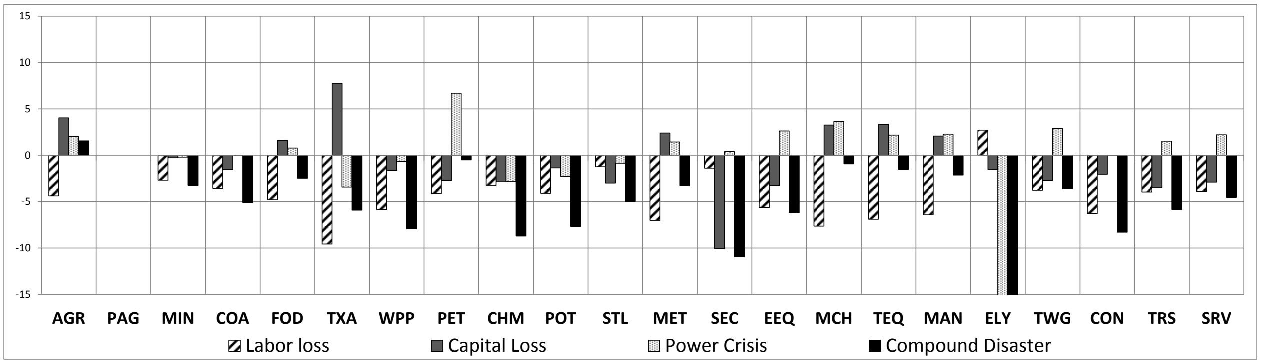

Figure 3.3.4: Impact on Sectoral Exports (changes from the base, %).

Such sectors as SEC (−10%) and EEQ (−3.2%) would be damaged heavily, mainly by capital losses, and their exports would decline, while exports would increase in some sectors, such as MCH (3.3%), TEQ (3.3%), MAN (2%), and TXA (7.8%). This contrast is consistent with the pattern of output changes reflecting their capital intensity, as shown in Table 3.1.1. This implies that Taiwanese exports would be affected directly by production capacity losses caused by a disaster.

3.3.2 Welfare Impact

In terms of the economic losses of the assumed earthquake, the TSSD reports the total loss estimates as 1,271 billion TWD, based on the construction costs of building stocks and infrastructure as well as damaged floor areas and materials (Table 2.1). In the CGE model experiments, the welfare losses are estimated with equivalent variations (EV) measured by decreased household consumption (Table 3.3.1).

Table 3.3.1: *Welfare Losses (Unit: billion TWD)*

Scenario	EV
Scenario 1 Labor loss	−291 (48%)
Scenario 2 Capital Loss	−252 (41%)
Scenario 3 Power Crisis	−83 (14%)
(Interaction term)	15 (−2%)
Scenario 4 Compound Disaster	−611 (100%)

The largest welfare loss among these factors would be caused by the labor loss. The power crisis would cause an additional 14% loss to the first two direct damage areas caused by the earthquake. The interaction term indicates the gap between the welfare impact of Scenario 4 and the sum of that in Scenarios 1–3. The total impact would reach 611 billion TWD, which is comparable to 50% of the TSSD estimates of the damaged stocks, and a loss of 75,590 TWD would be borne per household.

3.4 Concluding Remarks

Not every natural hazard necessarily turns into a huge disaster but every disaster contains some complex elements that can lead to a compound disaster with devastating results. The social and economic significance of disasters should be estimated to better prepare for a disaster while considering the context of individual regions that are affected. This study used a CGE model to quantify the economic consequences of a compound disaster in northern Taiwan, where the national capital and leading industries are located. The simulation results showed that as factor and energy intensities differed by sector, their respective vulnerabilities would also differ. Highly labor-intensive sectors, such as textiles, electronic equipment, and machinery, would be damaged most severely in the labor-loss scenario while capital-intensive sectors, such as semiconductors, would be harmed the most in the capital-loss scenario. This contrasting result implies that effective disaster prevention and risk management strategies need to be developed with due consideration of these industry characteristics.

In the power crisis scenario, power prices would rise sharply to 27% and would be reflected in a 1–2% rise in output price distributed nearly equally among sectors. This power crisis would add a 17% greater loss to the direct loss in capital and labor from the assumed earthquake. However, the power price rise would cause little negative impact on key sectors, such as semiconductors, electronic equipment, machinery, and transportation equipment. This leads to the important implication that these major sectors could survive in a power crisis, even without intentional resource mobilization. As long as the price mechanism worked correctly, a power price rise of 27% would suppress power demand by heavy power consumers and automatically mobilize power to these key sectors to maintain their production and exports.

While this study focused on the short-term impact of a compound disaster, it is also necessary to examine the implications of a compound disaster from a long-term perspective. A dynamic CGE model could be employed to examine what would happen to those key Taiwanese sectors in the recovery process. From an international economics perspective, a disaster would decrease the international competitiveness of those key sectors vis-à-vis neighboring Asian countries through offshoring. This could be examined with a world trade CGE model, as undertaken by Hosoe (2014).

Appendix 3.A Estimation of Capital and Labor Losses

In terms of capital loss assumption, the TELES reports building collapse rates in the r-th region as C_r (Table 3.2.1), while the study uses information of geographic concentration rates of the i-th industry in the r-th region $X_{i,r}$ (Table 3.A.1). Combining these two datasets, the regional and industrial building collapse rates can be calculated. However, buildings that are not collapsed or only partially collapsed sometimes cannot be for firms to operate. As the proportion (ratio) of fully- and partially-collapsed buildings was approximately 1:1 in Taiwan's 921 Earthquake (Lai and Chen, 2000), the estimated capital damage could be assumed to be twice as large as the original damage. Finally, the capital losses of the i-th industry in the r-th region $CL_{i,r}$ as $CL_{i,r} = X_{i,r} \times C_r \times 2$ (Table 3.A.2) could be computed. The total sectoral capital loss rate $\sum_r CL_{i,r}$ is shown in Table 3.2.2.

Table 3.A.1: *Geographic Concentration of Industry in terms of National Share* ($X_{i,r}$)^a *(%)*

Sector	Affected Regions									Other Regions
	Taipei City	New Taipei City	Taoyuan County	Hsinchu County	Hsinchu City	Keelung City	Miaoli County	Iilan County	Subtotal	
AGR	0.9	3.6	5.4	3.4	0.7	0.1	5.0	3.7	22.6	77.4
PAG	16.7	0.0	0.0	16.7	0.0	0.0	66.7	0.0	100.0	0.0
MIN	3.1	3.7	3.3	4.8	0.7	0.2	11.5	14.2	41.4	58.6
COA	16.1	5.4	3.6	1.8	1.8	1.8	8.9	19.6	58.9	41.1
FOD	4.5	9.8	6.9	2.2	1.3	0.7	2.3	3.5	31.2	68.8
TXA	5.6	21.3	10.6	0.6	0.6	0.4	1.7	2.7	43.5	56.5
WPP	12.1	25.3	6.4	1.1	1.5	0.3	2.3	1.5	50.8	49.2
PET	4.3	13.9	7.8	1.7	0.9	0.4	6.1	4.8	40.0	60.0
CHM	4.1	24.0	9.6	1.7	1.5	0.1	1.6	0.7	43.3	56.7
POT	4.0	19.9	8.1	3.1	4.0	0.6	7.6	3.0	50.4	49.6
STL	2.3	19.1	11.6	2.0	1.0	0.3	2.2	1.2	39.8	60.2
MET	2.0	22.7	7.4	1.3	1.4	0.4	1.3	0.9	37.4	62.6
SEC	6.5	36.1	24.3	5.7	4.5	0.6	1.7	0.6	80.0	20.0
EEQ	7.7	34.6	11.2	3.3	3.5	0.6	1.3	0.7	62.9	37.1
MCH	2.4	20.5	10.4	1.6	1.7	0.2	1.5	0.9	39.2	60.8
TEQ	2.2	12.6	9.8	1.9	0.6	1.0	0.9	0.4	29.3	70.7
MAN	5.4	15.8	6.9	1.5	1.9	1.6	1.7	2.3	37.1	62.9
ELY	5.0	9.2	4.5	3.1	0.8	1.1	4.5	3.6	31.8	68.2
TWG	6.7	15.1	7.8	2.2	2.2	1.7	4.5	3.9	44.1	55.9
CON	9.5	15.8	8.9	2.5	2.4	1.7	2.7	2.5	46.0	54.0
TRS	20.6	31.6	6.1	1.0	0.8	4.0	1.3	1.7	67.1	32.9
SRV	18.1	13.2	7.0	1.6	1.9	1.6	1.9	2.0	47.4	52.6

Note. Author's estimates using the TSSD and census of agriculture, industry, and business by the DGBAS (2011b). $^a X_{i,r} = \frac{business\ entity\ of\ sector\ i\ in\ region\ r}{total\ business\ entity\ of\ sector\ i}$

Table 3.A.2: *Capital Losses ($CL_{i,r}$) by Sector (%)*

Sector	Affected Region								Total
	Taipei City	New Taipei City	Taoyuan County	Hsinchu County	Hsinchu City	Keelung City	Miaoli County	Iilan County	
AGR	0.2	0.9	0.2	0.0	0.0	0.0	0.0	0.0	1.3
PAG	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2
MIN	0.8	0.9	0.1	0.0	0.0	0.0	0.0	0.1	1.9
COA	4.0	1.3	0.1	0.0	0.0	0.1	0.0	0.1	5.7
FOD	1.1	2.4	0.3	0.0	0.0	0.0	0.0	0.0	3.9
TXA	1.4	5.3	0.4	0.0	0.0	0.0	0.0	0.0	7.1
WPP	3.1	6.3	0.2	0.0	0.0	0.0	0.0	0.0	9.6
PET	1.1	3.5	0.3	0.0	0.0	0.0	0.0	0.0	4.9
CHM	1.0	6.0	0.4	0.0	0.0	0.0	0.0	0.0	7.4
POT	1.0	5.0	0.3	0.0	0.0	0.0	0.0	0.0	6.3
STL	0.6	4.7	0.4	0.0	0.0	0.0	0.0	0.0	5.8
MET	0.5	5.6	0.3	0.0	0.0	0.0	0.0	0.0	6.4
SEC	1.6	9.0	0.9	0.0	0.0	0.0	0.0	0.0	11.6
EEQ	1.9	8.6	0.4	0.0	0.0	0.0	0.0	0.0	11.0
MCH	0.6	5.1	0.4	0.0	0.0	0.0	0.0	0.0	6.1
TEQ	0.5	3.1	0.4	0.0	0.0	0.0	0.0	0.0	4.1
MAN	1.4	3.9	0.3	0.0	0.0	0.1	0.0	0.0	5.6
ELY	1.3	2.3	0.2	0.0	0.0	0.1	0.0	0.0	3.8
TWG	1.7	3.7	0.3	0.0	0.0	0.1	0.0	0.0	5.8
CON	2.4	3.9	0.3	0.0	0.0	0.1	0.0	0.0	6.8
TRS	5.2	7.9	0.2	0.0	0.0	0.2	0.0	0.0	13.5
SRV	4.6	3.3	0.3	0.0	0.0	0.1	0.0	0.0	8.2

Note. Author's estimates using the TSSD and census of agriculture, industry, and business. $CL_{i,r} = X_{i,r} \times C_r \times 2$.

We estimated regional labor loss rates in the total labor force (endowment) LL_r (Table 3.A.3) by combining the regional employment share SL_r (Table 3.A.4) with the national labor force affected by the building damage ($C_r \times 2$) as $SL_r \times C_r \times 2$. Adding these for all the regions, the total labor loss rate could be estimated as 7.4% (at the bottom of Table 3.A.3).

Table 3.A.3: *Estimated Labor Loss Rates in the Affected Region (LL_r) (%)*

Taipei City	2.8
New Taipei City	4.2
Taoyuan County	0.3
Hsinchu County	0.0
Hsinchu City	0.0
Keelung City	0.1
Miaoli County	0.0
Iilan County	0.0
Total	7.4

Note. $LL_r = SL_r \times C_r \times 2$.

Table 3.A.4: *Regional Share of Labor Endowment (SL_r) (%)*

Affected Region:	Taipei City	11.3
	New Taipei City	16.9
	Taoyuan County	8.3
	Hsinchu County	2.1
	Hsinchu City	1.8
	Keelung City	1.7
	Miaoli County	2.4
	Iilan County	2.0
Subtotal		46.5
Others		53.5

Source: Labor Force Statistics by County and Municipality, DGBAS (2007).

Note. $SL_r = \frac{Labor\ force\ in\ region\ r}{National\ Labor\ Endowment}$

Appendix 3.B Sensitivity Analysis

In CGE analysis, simulation results often depend on assumptions of key parameters, especially the elasticity of substitution/transformation in CES/CET functions. To examine the robustness of the results, sensitivity tests were conducted with respect to the elasticity of substitution among energy sources σ^e and Armington's (1968) elasticity of substitution/transformation σ_i/ψ_i. The results are shown below.

3.B.1 Sensitivity Analysis with Respect to Elasticity of Substitution among Energy Sources

We assumed alternative values, both smaller (0.7) and larger (1.3), for the elasticity of substitution in the energy composite production function σ^e. This elasticity describes the flexibility of substitution among various energy sources while the parameter value is assumed to be 1.1 for the simulations whose results are shown in the main text. The results indicated little sensitivity of the simulation results for nonenergy sectors while the predicted output changes in the energy sectors showed some differences in quantity but little in quality, with the exception of the petroleum sector (PET) in the 30% smaller elasticity case (Table 3.B.1).

3.B.2 Sensitivity Analysis with respect to Armington Elasticity

The second parameter examined was Armington's (1969) elasticity of substitution σ_i and ψ_i. The study perturbed them by 30% upward and downward while assuming the same shocks and found that the simulation results were affected hardly at all by the alternative assumptions (Table 3.B.2).

Table 3.B.1. *Results of Sensitivity Tests in terms of Sectoral Output Changes (∆Z/Z, %) and Welfare Impact (EV, billion TWD) with Respect to Elasticity of Substitution among Energy Sources*

Sector	**Smaller Elasticity Case $\sigma^e = 0.7$**				**Central Elasticity Case $\sigma^e = 1.1$**				**Larger Elasticity Case $\sigma^e = 1.3$**			
	Labor Loss	**Capital Loss**	**Power Crisis**	**Compound Disaster**	**Labor Loss**	**Capital Loss**	**Power Crisis**	**Compound Disaster**	**Labor Loss**	**Capital Loss**	**Power Crisis**	**Compound Disaster**
AGR	-4.4	-0.2	-0.1	-4.7	-4.4	-0.2	-0.1	-4.7	-4.4	-0.2	-0.1	-4.7
PAG	-3.4	-1.2	3.3	-1.4	-3.5	-1.2	3.5	-1.2	-3.5	-1.2	3.7	-1.1
MIN	-3.7	-2.0	-0.7	-6.3	-3.7	-2.0	-0.6	-6.2	-3.7	-2.0	-0.5	-6.1
COA	-3.6	-2.2	1.3	-4.7	-3.6	-2.2	1.0	-4.9	-3.6	-2.2	0.7	-5.2
FOD	-4.5	-1.4	-0.6	-6.4	-4.5	-1.4	-0.6	-6.4	-4.5	-1.4	-0.5	-6.3
TXA	-8.5	5.5	-3.9	-7.2	-8.5	5.5	-3.0	-6.5	-8.6	5.5	-2.4	-5.9
WPP	-5.0	-2.5	-0.6	-8.0	-5.0	-2.5	-0.5	-7.9	-5.1	-2.5	-0.3	-7.7
PET	-4.1	-2.9	7.2	-0.2	-4.2	-2.9	8.4	0.9	-4.3	-3.0	9.4	1.7
CHM	-3.5	-3.0	-2.7	-9.0	-3.5	-3.0	-2.2	-8.6	-3.5	-3.0	-1.8	-8.2
POT	-4.8	-3.1	-1.6	-9.3	-4.8	-3.1	-1.4	-9.1	-4.8	-3.1	-1.2	-9.0
STL	-3.1	-2.1	-0.4	-5.5	-3.2	-2.1	-0.2	-5.3	-3.2	-2.1	0.0	-5.2
MET	-6.3	0.6	0.9	-4.7	-6.3	0.6	1.1	-4.6	-6.3	0.6	1.2	-4.5
SEC	-1.5	-9.9	0.4	-10.9	-1.5	-9.9	0.4	-10.8	-1.5	-9.9	0.4	-10.8
EEQ	-5.5	-3.4	2.0	-6.7	-5.5	-3.4	2.0	-6.7	-5.5	-3.4	2.0	-6.7
MCH	-7.2	1.7	2.6	-2.9	-7.2	1.7	2.6	-2.9	-7.2	1.7	2.6	-3.0
TEQ	-6.2	1.1	1.0	-4.1	-6.2	1.1	1.0	-4.1	-6.2	1.1	1.1	-4.1
MAN	-5.5	-0.3	0.9	-4.9	-5.5	-0.3	0.9	-4.9	-5.5	-0.3	0.8	-4.9
ELY	-3.0	-3.1	-12.1	-17.7	-2.8	-3.0	-14.4	-19.8	-2.6	-3.0	-16.4	-21.5
TWG	-4.3	-3.6	3.5	-4.5	-4.5	-3.6	5.8	-2.4	-4.6	-3.6	7.5	-0.8
CON	-5.5	-3.9	-1.3	-10.4	-5.5	-3.9	-1.2	-10.4	-5.5	-3.9	-1.2	-10.4
TRS	-4.1	-3.5	0.6	-6.9	-4.1	-3.5	0.6	-6.9	-4.1	-3.5	0.6	-6.9
SRV	-4.2	-3.4	0.1	-7.4	-4.1	-3.4	0.1	-7.4	-4.2	-3.4	0.1	-7.4
Welfare	-291	-252	-85	-612	-291	-252	-83	-611	-291	-252	-81	-609

Table 3.B.2. *Results of Sensitivity Tests in terms of Sectoral Output Changes (ΔZ/Z, %) and Welfare Impact (EV, billion TWD) with Respect to Armington's Elasticity of Substitution/Transformation*

Sector	**30% Smaller Elasticity Case**				**Central Elasticity Case**				**30% Larger Elasticity Case**			
	Labor Loss	**Capital Loss**	**Power Crisis**	**Compound Disaster**	**Labor Loss**	**Capital Loss**	**Power Crisis**	**Compound Disaster**	**Labor Loss**	**Capital Loss**	**Power Crisis**	**Compound Disaster**
AGR	-4.4	-0.6	-0.2	-5.2	-4.4	-0.2	-0.1	-4.7	-4.4	0.1	0.0	-4.3
PAG	-3.6	-1.3	4.4	-0.5	-3.5	-1.2	3.5	-1.2	-3.4	-1.2	2.9	-1.6
MIN	-3.9	-2.1	-0.5	-6.5	-3.7	-2.0	-0.6	-6.2	-3.5	-1.9	-0.7	-6.0
COA	-3.6	-2.3	1.4	-4.7	-3.6	-2.2	1.0	-4.9	-3.5	-2.2	0.7	-5.2
FOD	-4.4	-1.7	-0.7	-6.7	-4.5	-1.4	-0.6	-6.4	-4.5	-1.2	-0.5	-6.1
TXA	-8.0	5.1	-2.3	-5.7	-8.5	5.5	-3.0	-6.5	-8.9	5.8	-3.6	-7.2
WPP	-4.9	-2.6	-0.3	-7.6	-5.0	-2.5	-0.5	-7.9	-5.1	-2.5	-0.6	-8.1
PET	-4.3	-3.0	9.1	1.4	-4.2	-2.9	8.4	0.9	-4.2	-2.9	7.8	0.4
CHM	-3.6	-2.9	-1.8	-8.1	-3.5	-3.0	-2.2	-8.6	-3.4	-3.2	-2.5	-8.9
POT	-4.9	-3.2	-1.2	-9.2	-4.8	-3.1	-1.4	-9.1	-4.8	-3.0	-1.5	-9.1
STL	-3.4	-1.8	0.0	-5.1	-3.2	-2.1	-0.2	-5.3	-3.0	-2.3	-0.4	-5.5
MET	-5.9	0.2	1.2	-4.5	-6.3	0.6	1.1	-4.6	-6.6	0.9	1.0	-4.7
SEC	-1.5	-9.8	0.5	-10.7	-1.5	-9.9	0.4	-10.8	-1.5	-10.0	0.3	-11.0
EEQ	-5.5	-3.0	2.1	-6.3	-5.5	-3.4	2.0	-6.7	-5.6	-3.7	1.9	-7.1
MCH	-6.8	1.3	2.4	-3.2	-7.2	1.7	2.6	-2.9	-7.4	2.0	2.7	-2.8
TEQ	-5.9	0.5	0.8	-4.5	-6.2	1.1	1.0	-4.1	-6.4	1.5	1.2	-3.8
MAN	-5.3	-0.6	0.7	-5.1	-5.5	-0.3	0.9	-4.9	-5.6	-0.1	1.0	-4.7
ELY	-2.8	-3.0	-14.3	-19.6	-2.8	-3.0	-14.4	-19.8	-2.8	-3.0	-14.6	-19.9
TWG	-4.5	-3.6	5.9	-2.4	-4.5	-3.6	5.8	-2.4	-4.5	-3.6	5.8	-2.4
CON	-5.5	-3.9	-1.3	-10.5	-5.5	-3.9	-1.2	-10.4	-5.5	-3.9	-1.2	-10.4
TRS	-4.1	-3.4	0.5	-6.9	-4.1	-3.5	0.6	-6.9	-4.1	-3.6	0.6	-6.9
SRV	-4.2	-3.4	0.0	-7.4	-4.1	-3.4	0.1	-7.4	-4.1	-3.4	0.1	-7.3
Welfare	-291	-251	-82	-609	-291	-252	-83	-611	-291	-254	-83	-612