A General Equilibrium Assessment on a Compound Disaster in Northern Taiwan

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Abstract

We analyze the economic impact on key sectors of a compound disaster in Taiwan. While Taiwan has high-tech export-oriented industries such as semiconductors and electronic products, three out of four nuclear power plants are located in the at-risk areas close to its capital city with industrial agglomeration. We use a computable general equilibrium (CGE) model to simulate a compound disaster in northern Taiwan. We consider the individual disaster components of labor loss, capital loss, power crisis, and finally combine them to simulate a compound disaster comprehensively. The simulation results show that Taiwan's key sectors such as semiconductor and electric equipment would be affected severely by capital and labor losses but not by the power crisis. This implies that no electric power allocation would be needed for these industries although we are often tempted to do so in emergencies.

Keywords: Compound Disaster, Disaster Risk Management, Computable General Equilibrium, Electricity, Energy

JEL Classification: D58, Q54, L52

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1. Introduction

1.1 Risks and Concerns of a Compound Disaster

East Asia and the Pacific comprise the most frequently 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; UN & 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, for 99% of its land and population are exposed to risks while 73% of the total area and population are at high mortality risk from more than three hazards (World Bank, 2005). Worldwide, Taiwan is ranked as the most vulnerable and is followed by Costa Rica, Vanuatu, and the Philippines.

Taiwan is a trade-orientated country with an external trade volume over 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 1.1. A disaster can affect not only production but also exports by destroying primary factors and disrupting their supply chains.

Table 1.1. *Profiles of Industries 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
Electric equipment	EEQ	5.0%	1.9%	0.34	4.40
Machinery	MCH	4.0%	0.8%	0.24	4.05
Transport 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
Service	SRV	34.2%	22.6%	0.45	1.91

Note. [a]Energy goods used for industrial production. [b]Energy goods used for household consumption. [c]Share of electricity input cost in total production costs. [d]The capital intensity is defined as a portion of remuneration of capital in total sectoral value added. [e]Armington's (1969) elasticity of substitution, provided in GTAP Database, version 8.

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

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 US$14,100 million, which ranked tenth among worldwide disasters in terms of economic loss between 1983 and 2013. In the fatality and losses estimation, the Ministry of The Interior reports 2,321 deaths and 82,238 households and buildings partially or fully damaged by the debris from collapsed buildings and mountain landslides from the 921 Earthquake.[1] 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, that is located in an area 120 km away from the epicenter. This caused the loss of TW$16,700 million (US$538.7 million in 1999 value) in semiconductor manufacturing and further affected the annual GDP by -0.24% (Mai, Yu, Sun, Lin, Wang, Chen et al., 1999). The concern about a compound disaster with nuclear power plants in Taiwan was heightened by the Great East Japan Earthquake 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 out of its four nuclear plants built on the coastline within the 30-km radius zone from the capital city of Taipei with its 5.5 million inhabitants.

1.2 Literature Survey

DRM studies started just recently and thus are scant for Taiwan despite their importance; most existing studies on seismic disasters focus on the losses of building and life, not on losses in economic activities. Moreover, given the above-mentioned situation that the economy faces, disaster risk assessments considering a single disaster do not suffice. Simulations with good details of industrial activities 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, & Tsai, 2006). TELES provides estimates of direct damages in terms of the number of deaths, injured people, and collapsed buildings caused by an earthquake with the magnitude and location that the user stipulates. Based on TELES, Lin, Kuo, Shaw, Chang, & Kao (2012) used an input-output (IO) model to estimate the impact of two types of earthquakes in north and northeast Taiwan on its economy and found that northern Taiwan would be affected more severely. Their results suggested that the government should make it a top priority to encourage manufacturing sectors to implement earthquake mitigations, such as a seismic retrofit, or to provide a seismic evaluation, which can enable firms to engage in mitigation voluntarily (Rodríguez-Vidal, Rodríguez-Llanes, & Guha-Sapir, 2012). However, these existing

[1] 921 Earthquake Knowledge Base Guide: http://921kb.sinica.edu.tw/archive/dgbas/dgbas05.html

studies considered only a single and static disaster event while omitting risks and possible troubles in nuclear power plants.

Anticipating and having experienced huge earthquakes, researchers have conducted many studies about Japan. For example, Tsuchiya, Tatano, & Okada (2007) and Tatano & Tsuchiya (2008) used a spatial CGE model 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, & Wei (2008) used a spatial CGE 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 other regions besides the earthquake-stricken regions, especially where megalopolis cities are located. As for other spatial CGE model applications, Koike, Tavasszy, Sato, & Monma (2012) developed a RAEM-Light CGE model to make a closer look at smaller-scale regions of municipalities and then analyzed the benefit of road networks in the presence of natural disasters.

In the context of the 2011 Great East Japan Earthquake, Yamazaki & 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 the 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 and investigated 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 such major Taiwanese industries as semiconductor and electronic equipment manufacturing. However, such economic risk assessments on nuclear and power shortage as Yamazaki & Takeda (2013) and Hosoe (2014) done for Japan with a CGE model have never been done for Taiwan.

Under the above-mentioned circumstances, which industries would be severely affected by what kind of factors in a major earthquake? If a power crisis follows the earthquake, would we need to allocate power supply, especially to such key industries as semiconductors, to support their production and exports? To answer these questions, we develop a CGE model and quantify the economic impact of a compound disaster made of a huge earthquake causing direct losses of (a) labor force and (b) physical capital, and the subsequent power crisis with (c) a shutdown of nuclear power and substitution with thermal power. Finally, these are considered simultaneously in a (d) simulation of a compound disaster. Our simulation results will show that Taiwan's major industries of semiconductors, electronic equipment, and steel would be negatively affected by physical losses of capital and labor but not by the power crisis. On the other hand, textiles and apparel, chemical, and pottery industries would be vulnerable to the power crisis.

This paper proceeds as follows. In Section 2, the model and methodology will be introduced, as will the assumptions and scenarios. In Section 3, the interpretation of empirical results will be made, and the concluding section will suggest policy implications with future extensions.

2. Methodology

2.1 Model Structure

A CGE model is a useful framework to analyze the economic impact of natural hazards and its policy response at micro and macro levels (Rose & Guha, 2004; Rose & Liao, 2005). Our CGE model is a multi-market simulation model based on the optimization behavior of individual households and firms, and their competition in markets following the standard CGE model developed by Hosoe, Gasawa, & Hashimoto (2010). We extended their model by describing substitution among various energy sources à la Hosoe (2006; see Figure 2.1). Our analysis with a multi-sectoral CGE model sheds a clear light on key Taiwanese industries such as semiconductors and electronic equipment. Our model distinguishes 22 sectors based on Taiwan's 2006 input-output table by DGBAS (2011a).

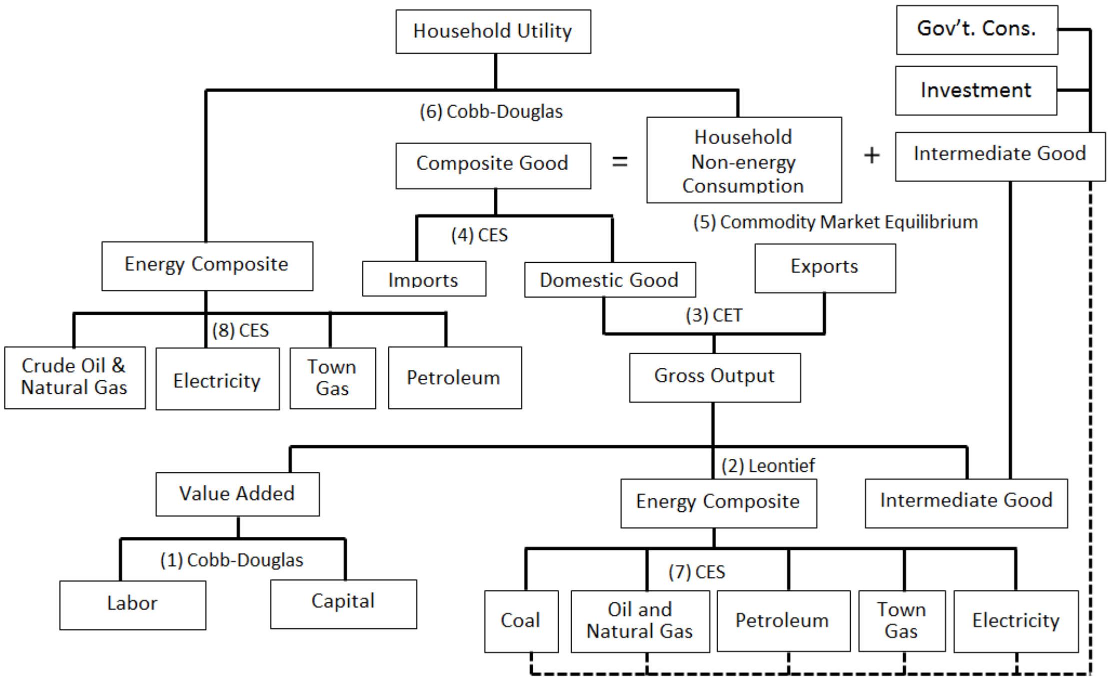


Figure 2.1. Model Structure of the CGE Model.

This model includes the following specifications. First, substitution between capital and labor is assumed in value added production with a Cobb-Douglas type production function (parenthetically labeled 1 in the figure). A Leontief type function (2) is employed for a production function of gross output, which is made up with value added, intermediate input, and an 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 intermediate input, while the household utility depends on consumption of various non-energy goods and an energy composite (6).

Next, the energy composite for non-energy sectors is made from these four energy goods and coal while we do not assume any 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 input-output table for 2006 (DGBAS, 2011a) while we use the Armington elasticity of substitution provided by the GTAP Database version 8 (Hertel, 1997) and assume

1.1 for the elasticity of substitution among energy goods.[2]

2.2 Compound Disaster Scenario

In this study we consider 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 contribution and significance of these impact components in a compound disaster in detail, we separately assume (a) labor loss, (b) capital stock loss, (c) a power crisis caused by the shutdown of nuclear power plants, and then we combine these three in (d) a compound disaster (the accumulation of all the scenarios above).

To set up a hypothetical scenario, we first assume the location and magnitude of an earthquake. In this study, we focus 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 its shallowness and the movement of subterranean magma near Taiwan's capital, Taipei City, and three nearby nuclear power plants (Figure 2.2). Feeding these assumptions into TELES/TSSD[3], we can estimate the direct damages caused by this assumed earthquake (Table 2.1).

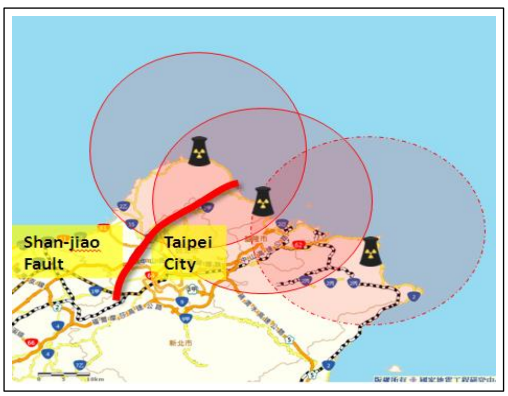


Figure 2.2. Geographical locations of capital, the Shan-jiao fault (red line) three nuclear power plants (black cooling towers), and the 30-km radius of nuclear power plants (translucent red ovals). Adopted from National Center for Research on Earthquake Engineering, Taiwan Seismic Scenario Database (TSSD).

[2] We conducted sensitivity tests with respect to these two elasticity parameters and found little qualitative difference in our simulation results. Details are shown in Appendix B.

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

Table 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: TW$1,271 billion		
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 our simulations; details are discussed below. Data retrieved from the Taiwan Seismic Scenario Database (TSSD).

Regarding capital loss estimates, TSSD reports building collapse rates in the r-th region, C_r (Table 2.1). We combine this information 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 2.2). The details of our estimation process of these shocks are shown in Appendix A.

Table 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	Electric equipment	- -	−11.0%	- -	−11.0%
MCH	Machinery	- -	−6.1%	- -	−6.1%
TEQ	Transport 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	Service	- -	−8.2%	- -	−8.2%
Labor Loss		−7.4%	- -	- -	−7.4%

Note. Calculated and assumed by author. Details of the respective estimation processes are shown in Appendix 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, TSSD indeed provides estimates of the number of dead and injured. However, labor losses could be caused not only by such death or injury but also by people's unemployment or unavailability due to damaged buildings or commuting troubles. Eventually, the number of dead and injured estimated by TSSD is only 0.1% of the population in the affected region, which does not fully reflect the reality of a disaster from the viewpoint of disrupted economic activities. Therefore, in our study, the decrease of labor is estimated on the basis of an *effective* disruption that could be caused by the building damage as discussed above.

The electric power sector was assumed to suffer not only the damage of its physical capital in the earthquake but also the shutdown of all of its 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 of nuclear power plant assets in the total assets of the Taiwan Power Company (2012) on top of its capital loss from the earthquake that was discussed earlier. The power sector is also assumed to (b) replace its 18.4% of power generated originally by 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 our model. To mimic the inter-fuel substitution, we manipulate the input requirement of fossil fuels so that the additional power generation with the fossil fuels can fully cover the lost power from nuclear power generation (Table 2.3).

Table 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. Taiwan Power Company for Actual and the authors' estimates for the counter-factual scenario.

The four scenarios are considered to quantify the impact of these three individual risk factors and their combination (Table 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 substitution of nuclear power with thermal power. Although these three would not occur separately in reality, individual examination of each disaster factor helps us to better investigate their impact on the Taiwanese economy. Scenario 4 demonstrates the accumulated impact of these three to depict a compound disaster.

3. Simulation Results

3.1 Sectoral Impact

In Scenario 1 of labor losses, all sectors would suffer with some but not large sectoral variations (Figure

3.1), partly because labor is mobile among sectors and partly because there are variations of capital/labor intensity by sector (Table 1.1). For example, the losses would be the most serious in TXA (-8.5%), which shows a high labor intensity. In Scenario 2 of capital damage, while most sectors would experience output decreases of 1% to 3%, the largest loss would occur in SEC (-9.9%). This is due to its very high capital intensity and its 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, sectors such as TXA, MCH and TEQ would gain. They are relatively labor-intensive industries and thus could benefit from hiring more workers released by those severely declining sectors.

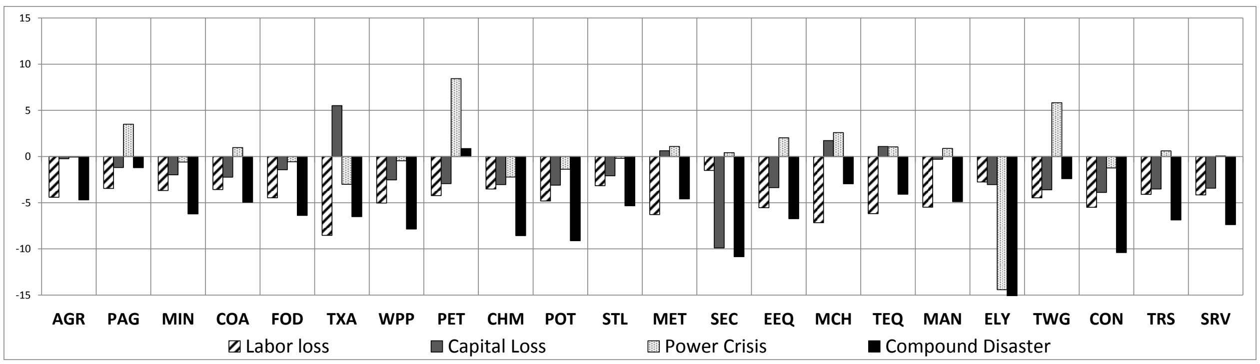


Figure 3.1. Impact on sectoral output (changes from the base, %). The output decline in ELY would be -19.8% in the Compound Disaster Scenario.

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 significantly increase because of increased demand as substitutes for nuclear power. The output of ELY would drop by 14.4% due to the loss of its nuclear capacity. The power charge rise would reach 27% and would be transmitted into price rises in manufacturing products by 1-2% (Figure 3.2). Among these manufacturing products, TXA and CHM would see their output decrease by 3.0% and 2.2%, respectively, due to this sharp increase in power charges. In contrast, EEQ and MCH would see their output increase because they are not as heavily dependent on electric power as intermediate input for their production processes. SEC would be affected only marginally despite the sharp power charge increase.

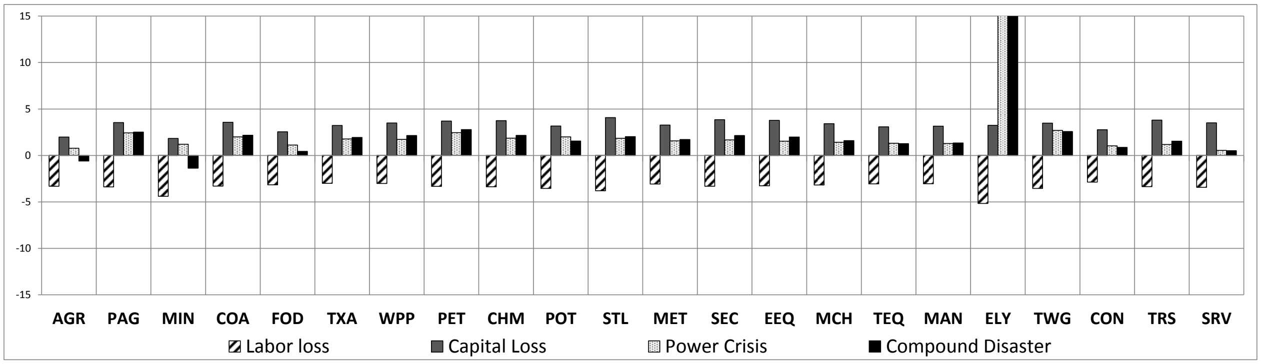
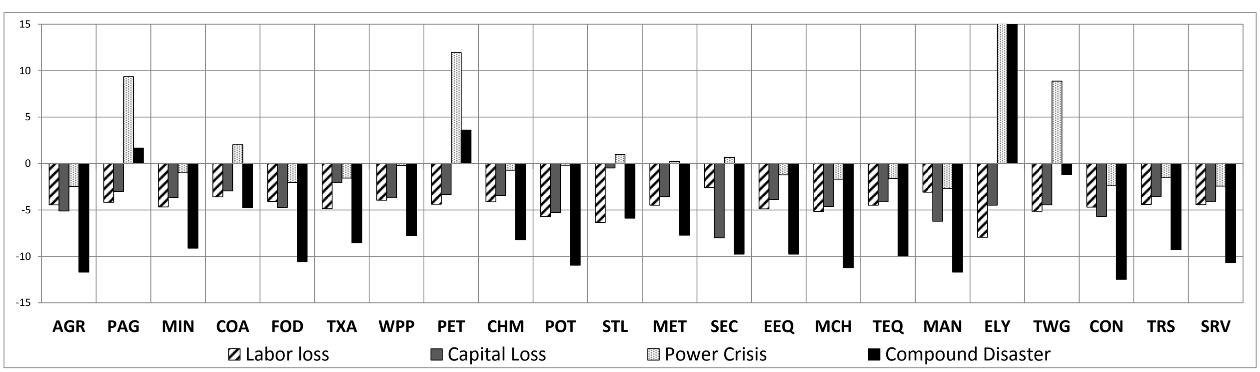


Figure 3.2. Impact on sectoral output prices (changes from the base, %). The price rise in ELY would be 26.7% and 24.9% in the Power Crisis and the Compound Disaster Scenarios, respectively.

The compound disaster, Scenario 4, assumes all the shocks of labor, capital loss, and a power crisis after the seismic disaster. While all the non-energy sectors would suffer losses of 5% or larger, the sources of their losses would differ as shown above. Significant losses would be seen in Taiwan's largest industries of SEC (-10.8%) and EEQ (-6.7%) 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 generally decrease because of the disrupted domestic production and final demand affected by the income loss (Figure 3.3). The sectoral exports are affected differently according to their input intensity of labor, capital, and electricity. Such sectors as TXA (-9.6%), MET (-7.0%), MCH (-7.6%), TEQ (-6.9%), and MAN (-6.4%) would see their exports decrease mainly due to labor losses (Figure 3.4). Their changes match those of their domestic output.[4]



[4] A large change of exports and imports of electricity is shown in Figures 3.3–3.4. They are consumption of electricity by foreigners and by Taiwanese abroad and are negligibly small. Therefore, these results have little significance in our analysis.

Figure 3.3. Impact on sectoral imports (changes from the base, %).

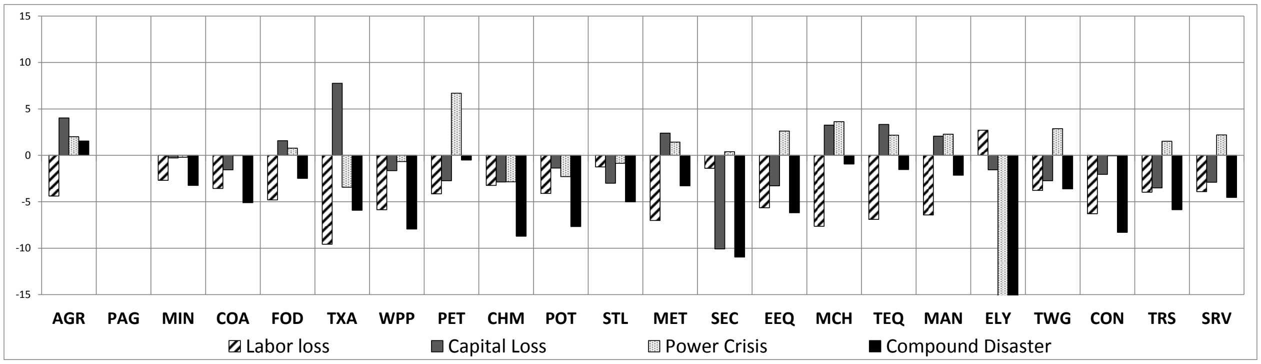


Figure 3.4. Impact on sectoral exports (changes from the base, %).

The sectors such as SEC (-10.0%) and EEQ (-3.2%) would be heavily damaged, mainly by capital losses, and would see exports decline, while some sectors would see increased exports, such as MCH (3.3%), TEQ (3.3%), MAN (2.0%), and TXA (7.8%). This contrast is consistent with the pattern of the output changes reflecting their capital intensity shown in Table 1.1. This implies that Taiwanese exports would be directly affected by losses of its production capacity due to a disaster.

3.2 Welfare Impact

In terms of the economic losses of the assumed earthquake, TSSD reports the total loss estimates as TW$1,271 billion, based on the construction costs of building stocks and infrastructure as well as the damaged floor areas and materials (Table 2.1). In our CGE model experiments, we estimate welfare losses with equivalent variations (EV) measured by decreased household consumption (Table 3.1).

Table 3.1. *Welfare Losses (Unit: TW$ billion)*

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 TW$611 billion, which is comparable to 50% of the TSSD estimates of the damaged stocks, and TW$75,590 (US$2,557 in 2013 value) loss would be borne per household.

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. We need to estimate the social and economic significance of disasters to better prepare for a disaster while considering the contexts of affected regions. We used a CGE model to quantify economic consequences of a compound disaster in northern Taiwan, where the national capital and leading industries are located. Our simulation results showed that as factor and energy intensity differed by sector, their respective vulnerabilities would also differ. Highly labor-intensive sectors such as textiles and apparel 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 contrast implies that effective disaster prevention and risk management strategies need to be developed with due consideration of those characteristics of industries.

In the power crisis scenario, a sharp rise of power charges would reach nearly 30% and would be reflected in a 1-2% output price rise nearly equally distributed among sectors. This power crisis would add a 14% larger loss to the direct losses in capital and labor from the assumed earthquake. However, this power charge rise would cause little negative impact on such key industries as semiconductors, electric equipment, machinery, and transportation equipment. This brings us to the important implication that these major industries could survive in a power crisis even without intentional resource mobilization. As long as the price mechanism worked correctly, a power charge rise by 27% would suppress the power demands by heavy power consumers and automatically mobilize power to these key industries to maintain their production and exports.

While this study is focused on the short-term impact of a compound disaster, we also need to examine implications of a compound disaster from a long-term perspective. We can employ a dynamic CGE model and examine what would happen to those key Taiwanese industries in the recovery process. From an international economics perspective, a disaster would decrease international competitiveness of those key industries vis-à-vis neighboring Asian countries through offshoring. We can examine it with a world trade CGE model as done by Hosoe (2014).

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Appendix A: Estimation of Capital and Labor Losses

In terms of capital loss assumption, TSSD reports building collapse rates in the r-th region as C_r (Table 2.1), while we have information of geographic concentration rates of the i-th industry in the r-th region $X_{i,r}$ (Table A.1). Combining these two, we computed regional and industrial building collapse rates. However, sometimes buildings that are not collapsed or just partially collapsed cannot be used for operation of firms. As the proportion (ratio) of fully- and partially-collapsed buildings was approximately 1:1 in Taiwan's 921 Earthquake (Lai & Chen, 2000), we thus assumed that the estimated capital damage was twice as large as the original damage. Finally, we computed 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 A.2). The total sectoral capital loss rate $\sum_r CL_{i,r}$ is shown in Table 2.2.

Table A.1: *The Geographic Concentration of Industry in 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. Authors' estimates with TSSD and Census of agriculture, industry and business by DGBAS (2011b).

[a] $X_{i,r} = \frac{business\ entity\ of\ sector\ i\ in\ region\ r}{total\ business\ entity\ of\ sector\ i}$

Table 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 with TSSD, 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 A.3) by combining the regional employment share SL_r (Table A.4) with the national labor force affected by the building damages ($C_r \times 2$) as $SL_r \times C_r \times 2$. Summing these for all the regions, we estimated the total labor loss rate as 7.4% (at the bottom of Table 2.2).

Table 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 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

Note. Labor Force Statistics by County and Municipality, DGBAS (2007). $SL_r = \frac{Labor\ force\ in\ region\ r}{National\ Labor\ Endowment}$

Appendix 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 our 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. Results are shown below.

B.1 Sensitivity Analysis with Respect to the 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 we assigned the parameter value of 1.1 for the simulations whose results are shown in the main text. The results indicated little sensitivity of our simulation results for non-energy 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 B.1).

B.2 Sensitivity Analysis with respect to the Armington Elasticity

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

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

Sector	Smaller Elasticity Case σ^e =0.7				Central Elasticity Case σ^e =1.1				Larger Elasticity Case σ^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 B.2. *Results of Sensitivity Tests in terms of Sectoral Output Changes (ΔZ/Z, %) and Welfare Impact (EV, bil. TW$) 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