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Using virtual laboratories for disaster analysis – a case study of Taiwan

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ABSTRACT

Due to its geographic location, Taiwan frequently experiences severe natural disasters (for example earthquakes and typhoons) that significantly interrupt business operations and subsequently cause extensive financial losses. Prior work on economic losses resulting from such natural disasters in Taiwan has not considered regional and sectoral spillover effects. In this work, we estimate the economic impacts resulting from the 1999 Chichi earthquake, the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi. We do so in the new TaiwanLab, a collaborative virtual laboratory that is capable of generating a time-series of subnational multiregional input–output (MRIO) tables, capturing interregional transactions among 267 sectors across Taiwan's 22 city-counties. We identify critical economic sectors in regions of high vulnerability to natural disasters. Our research is, thus, a credible reference to decision-making that determines regional and sectoral prioritisation for damage mitigation, improved resiliency, and faster recovery schedules.

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Disaster; Taiwan; multiregional input–output analysis; MRIO; virtual laboratory

1. Introduction

The rapid industrialisation of Taiwan during the 1950s and 1960s created a prosperous industrial economy and transformed Taiwan into one of Asia's economic miracles, alongside Hong Kong, South Korea and Singapore. Since then Taiwan became a crucial part of the world economy, especially in high-tech manufacturing. In 2016, Taiwan was a key supplier in the world market for semiconductor manufacturing equipment, with roughly 25% of the market share (Blouin, 2017). For many years, Taiwan also leads the world in

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contract manufacturing of information and computer technology (ICT) equipment. High-tech manufacturing sites sprang up in many areas of Taiwan – Taipei, New Taipei, Taoyuan, Miaoli, Hsinchu, Taichung, Tainan and Kaohsiung – ultimately comprising about a third of Taiwan's gross domestic product (GDP). Manufacturing, thus, replaced agriculture as the island's leading sector. In fact, in 2016 the latter contributed only 2% of GDP (National Statistics, 2017e).

Taiwan's prosperous economy is often interrupted by severe natural disasters. The 1999 Chichi earthquake, for example, damaged many business facilities and resulted in extensive financial loss across the breadth of the island's economy. Ultimately, 100,000 people become homeless, 9,000 industrial sites were damaged, and 4 million households lacked water supply; a power blackout covered north and central Taiwan for ten days. The Chichi earthquake resulted in a 0.5% correction in the island's 1999 GDP growth (Dong et al., 2000).

Taiwan frequently experiences natural disasters. This results from its geographic position within the circum-Pacific seismic zone. Indeed, record shows that 20,000 earthquakes occurred there between 1604 and 1988 (Chang, 1996). Seismic activity on Taiwan was particularly high from 1991 to 2014 at 18,000 earthquakes per year (Central Weather Bureau, 2017a). On 6 February 2018, an earthquake that hit 6.4 on the Richter scale struck Hualien, injuring more than 100 people (The Guardian, 2018).

From 1911 to 2015, a total of 360 typhoons made landfall in Taiwan – an annual average of 3 to 4 typhoons (Central Weather Bureau, 2017b). Taiwan's vulnerability to such devastating natural disasters necessitates comprehensive disaster impact assessments to support damage prevention and economic recovery.

1.1. Review of prior work on input–output-based disaster analysis

Input–output (IO) based disaster assessments enable the quantification of both the direct and the indirect supply-chain impacts of a disaster. Since Cochrane (1974) a plethora of publications has focussed on disaster analysis using IO tables and IO analysis, specifically. In the last decade, *Economic Systems Research* has featured two special issues on the topic (Okuyama, 2007; Okuyama and Santos, 2014). Many variants of IO-based models have emerged that extend the fundamental IO calculus to incorporate temporal and spatial scales (Santos and Haimes, 2004; Haimes et al., 2005; Donaghy et al., 2007; Yamano et al., 2007). But most published IO disaster studies use a single-region IO model; they thus omit the assessment of interregional and international spillover and feedback effects (Miller and Blair, 2009). This is largely due to the inherent difficulties in constructing subnational MRIO tables; intra-national interregional trade data tend not to be collected.

The availability of a global/subnational multiregional IO (MRIO) table is needed to depict the interactions between different regions. At a global level, for example, the construction of MRIO databases (Tukker and Dietzenbacher, 2013) enabled Schulte in den Bäumen et al. (2014) to assess the multi-country economic impact of Coronal mass ejections (CMEs) on electrical grids. MacKenzie et al. (2012) and Arto et al. (2015) used the OECD IO table and World Input–Output Database (WIOD), respectively, for measuring the global economic impacts of the 2011 Japanese earthquake and tsunami. At a subnational level, researchers used multiregional models to analyse the spillover effects of three floods in Rotterdam, The Netherlands (Koks and Thissen, 2016), flooding in eastern and southern Germany (Schulte in den Bäumen et al., 2015), Hurricane Katrina's landfall in Louisiana, USA (Hallegatte, 2008), and a tropical cyclone in Queensland, Australia (Lenzen et al., 2019).

In this work, we demonstrate the functionality of MRIO framework for the assessment of spillover effects resulted from natural disasters using a case study of Taiwan. There have been prior attempts to quantify the effects and impacts of natural disasters in Taiwan. Most of the research that touches upon the social and economic dimensions of post-disaster human behaviour. It discusses the consequent reduction in worker productivity (Tsai et al., 2012), the psychological and behavioural change as embodied in fear and risk (Huan et al., 2004), the loss and recovery of tourism (Liu, 2014), and the assessment of risk and management on the hospitality sector and high-tech manufacturing (Tsai and Chen, 2010). Lin et al. (2012) used an MRIO model of Taiwan to estimate the economic impacts of two scenario earthquakes for a year.

Despite all of the above, a comprehensive, detailed assessment of natural disasters in Taiwan remains lacking. The importance of this gap cannot be overemphasised due to the high rate of disaster occurrence, as well as the tremendous economic losses and uncertainty that accompany each event. The sheer mass of the above work points to the importance of understanding intersectoral consequences in a disaster context, in particular for communities and/or organisations that need public assistance and policy attention. The indirect losses of sectors and regions can only be understood well through the interregional modelling approach. Hsu et al. (2013), for example, estimate the earthquake vulnerability of hi-tech manufacturing in Taiwan; but they fail to assess economic losses emanating from disaster-generated supply-chain disruptions.

1.2. This study

The occurrence and consequences of disasters tend to be highly localised. Combine this with an equally differentiated regional economy, and it becomes clear that assessing indirect effects from disasters in Taiwan requires a regionally and sectorally detailed data foundation. The specific regional and sectoral nature of disaster impacts necessitate a particular subnational MRIO table that features a) very recent data, and b) detail where disaster impacts are expected to be significant. But in Taiwan, and elsewhere, existing MRIO databases tend to be insufficiently spatially detailed to enable meaningful disaster analyses, not to mention the required sectoral resolution and vintage. Moreover, whilst studies on losses resulting from natural disasters usually focus on leftover capacity (UNESCAP, 2018), we examine alternative definitions of loss in terms of value added. This is the key novelty of our work: We develop[1] a new virtual laboratory – the *TaiwanLab* – that is capable of constructing detailed subnational MRIO tables for Taiwan for the period 1990–2016 that can be tailored to a set of specific disaster analysis questions. A virtual lab is an innovative and compelling solution to the current gap of flexible and timely MRIO tables for disaster analysis. Taiwan is a great illustration of this innovation, but also interesting one, because the country is small and unexpectedly varied, especially with regard to the vulnerability of its regions to disasters and their impacts.

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[1] Based on a collaboration between the University of Sydney in Australia and the National Cheng Kung University in Taiwan.

Figure 1. Map of Taiwan.

A virtual laboratory is a collaborative research platform that enables the: a) timely update of (multiregional) IO tables, a process that is otherwise a tedious and an expensive, b) development of subnational IO tables that can be used for studying disaster-related spillovers and feedback effects across regions in a country; and c) construction of a time-series of IO tables, which allows the study of disasters across time (Lenzen et al., 2017). A virtual laboratory also allows users to customise their MRIO tables to specific regions or sectors, and integrate additional region- and sector-specific information. These capabilities assist users in adapting their modelling framework to specific natural disasters, as these can occur in specific, varying regions, and hit only particular sectors. The TaiwanLab is built at high regional and sectoral detail, generating a time-series of MRIO tables consisting of 22 city-counties (see Figure 1) and 267 economic sectors (see Appendix 1 and 2.2). Because of this unsurpassed detail, the TaiwanLab is able to capture linkages between disaster-hit sectors and regions, and the remainder of the economy. At the time of this writing, no such MRIO database exists for Taiwan.

Herein, we describe how using the TaiwanLab advances comprehensive regional assessments of disaster impacts. To this end, we apply the TaiwanLab to four case studies of natural disasters in Taiwan that have so far not been analysed. We include Taiwan's deadliest earthquake as well as its deadliest typhoon in modern history – the 1999 Chichi earthquake and the 2009 typhoon Morakot. We add to those the most recent earthquake and typhoon at the time of this writing – the 2016 Tainan earthquake and the 2016 typhoon Megi. These four cases are diverse in the way they affected regions and sectors. The earthquakes usually hit western Taiwan where the island's financial and industrial centre are located, while the typhoons land mostly in the agricultural locations in eastern Taiwan.

This diversity is meant to showcase the utility of the TaiwanLab. Our contribution to disaster analysis is therefore twofold: a) using a virtual lab to achieve the regional and sectoral detail necessary to undertake disaster analysis at sufficient resolution, and b) analysing four disasters in Taiwan that have never been studied before. We use a method proposed by Steenge and Bočkarjova (2007) to determine regional and sectoral spillover effects.

2. Methods

2.1. MRIO database

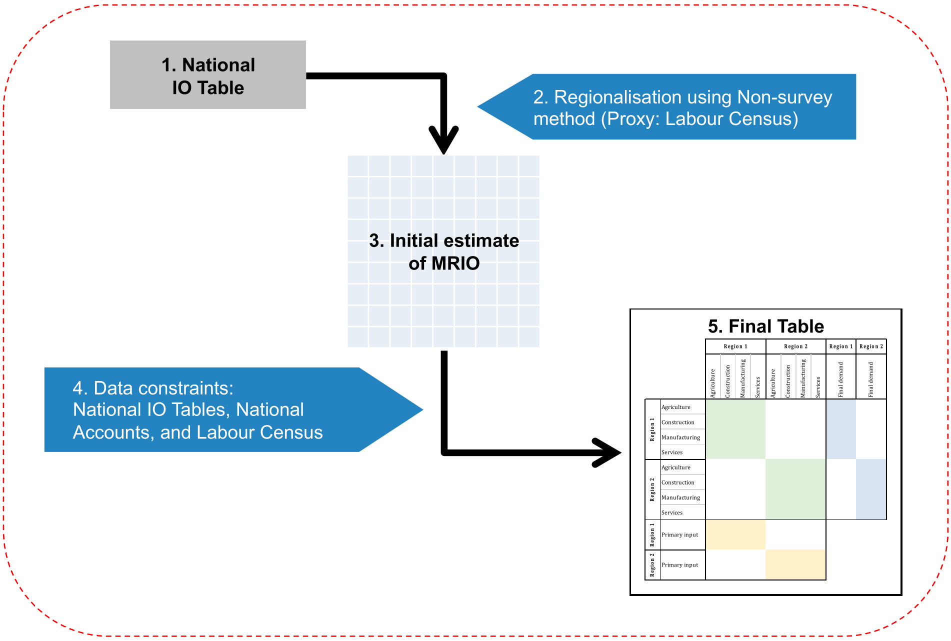
2.1.1. Virtual laboratory technology

The TaiwanLab is a virtual laboratory built in a cloud-computing environment, similar to those hosting the Australian Industrial Ecology Virtual Laboratory (IELab; Lenzen et al., 2017), the Indonesian IELab (Faturay et al., 2017), the Chinese IELab (Wang, 2017) and the Japanese IELab (Wakiyama et al., 2019). As with other virtual laboratories, the TaiwanLab supports remote access, harmonised data storage, automatic data processing, and flexible regional and sectoral classifications. Lab users are able to access, update or integrate a number of data sources, and choose their preferred regional and sectoral classifications, to suit their specific disaster case studies. These characteristics overcome the difficulty and time-consuming process of developing subnational MRIO tables.

The first step in constructing a subnational MRIO database in the TaiwanLab (see Figure 2) is to obtain national IO tables at the highest possible detail. Second, these national IO tables are then disaggregated into subnational MRIO tables using nonsurvey regionalisation methods (Sargento et al., 2012), which are widely used techniques for generating sub-regional MRIO tables using national IO tables as a starting point. The TaiwanLab is currently equipped with ten different nonsurvey methods that can be flexibly selected by users (see Appendix 4). We choose the cross-hauling-adjusted regionalisation method (CHARM) over the traditional method (e.g. the simple location quotient, SLQ) to regionalise the Taiwan national IO table. CHARM allows simultaneous export and import of a commodity (cross-hauling) and avoids some downward bias in interregional trade transactions (Többen and Kronenberg, 2015). Cross-hauling is the rule rather than the exception, as implicitly assumed by SLQs. The MRIO tables are tailored into 267 sectors, yet the industrial groups are sufficiently large to accommodate heterogeneous products. For example, manufacture of textile includes the conversion of fibre into yarn, and yarn into fabric. For a comparison to CHARM, we present the Taiwan MRIO table using SLQ in Appendix 5.

The regionalisation of the national IO tables into subnational MRIO tables is accomplished using a proxy quantity describing the economic structure of a region in comparison to the nation. Labour data are the preferred candidate for this proxy quantity since they are available at a satisfactory level of disaggregation for all cities and counties, and for all sectors. Taiwan's regional employment data capture 22 city-counties and 267 sectors. This detail is used as the root classification serving as a feedstock during the MRIO reconciliation process. The use of a root classification aims to consolidate various data classifications into a single classification so that all user-specific classifications can be derived from one and the same feedstock. To tailor the MRIO table to the users' specific questions, lab users select application-specific sectors and regions to be represented individually in the MRIO table, and aggregate other sectors and regions. For example, to investigate the effects of

Figure 2. Steps to construct MRIO tables in the TaiwanLab.



the 2016 Tainan earthquake, the important sectors are agriculture, livestock, forestry, and fishery products, whilst the important regions are Tainan, Kaohsiung and Pingtung. The tailoring process then proceeds via the user setting up concordance matrices that cast the root classification into the earthquake-specific classification. Detailed regional employment and Census data for agricultural industries in Tainan, Kaohsiung and Pingtung are then used to support the regionalisation of the MRIO table. In this way, the geography of Taiwan can be 'used' to inform specific disaster-related questions. In this study, four disasters are simultaneously examined, impacting virtually the entire Taiwanese economy, and every city/county. Therefore, we generated full MRIO tables at root classification, and then investigated the spillover effects of Taiwan natural disasters to all possible sectors and regions.

Third, based on the user's choice of sectors, regions and the nonsurvey regionalisation method, we extract the national and specific regional data that are needed to regionalise the national table. Most nonsurvey regionalisation methods, such as the location quotients and cross-hauling variants available to the TaiwanLab, apply regional weights – here derived from the labour census – to regionalise a national table. The user's choice of regionalisation method is independent of their choice of sectoral and regional classifications.

Fourth, the outcome of this regionalisation process is an initial estimate of the MRIO table. It is a preliminary estimate or prior to start a reconciliation process, in which balance conditions and a set of constraints are enforced. Reconciliation is carried out using an automatic system, known as AISHA (Automated Integration System for Harmonised Accounts, Geschke et al., 2014). A number of data sources are then used to simultaneously constrain the Taiwan MRIO tables, such as the series of national IO tables, national accounts, and the labour census (see Section 2.1.2 and Table 1).

Table 1. Primary data for the TaiwanLab.

Data	Years	Regions	Sectors	MRIO part constrained	Source
1. *National Input–Output Tables*					National Statistics (2017b)
a. 162 sectors	2001, 2006	1	162	ID, FD, VA	
b. 166 sectors	2011	1	166	ID, FD, VA	
2. *National Accounts*					National Statistics (2017e)
a. GDP by expenditure	1990–2016	1	6	FD, Exp, Imp	
b. GDP by sector	1990–2016	1	63	VA	
c. Gross output	1990–2016	1	63	GO	
d. Intermediate consumption	1990–2016	1	63	ID	
3. *Census*					
a. Industry and Service Census	2001, 2006, 2011	22	241	Proxy for regionalisation	National Statistics (2017d)
b. Agriculture, Forestry, Fishery and Animal Husbandry Census	2000, 2005, 2010	22	20	Proxy for regionalisation	National Statistics, (2017a)
c. Public Services and Education Census	2001, 2006, 2011	22	6	Proxy for regionalisation	National Statistics (2017c)

Notes: ID = Intermediate Demand, FD = Final Demand, VA = Value-Added, Imp = Import, Exp = Export, and GO = Gross Output. The text under column header 'MRIO part constrained' describes the specific MRIO elements that are constrained by the respective data source. The text 'Proxy for regionalisation' means that the respective data source was used in our approach when disaggregating the national IO tables into regions.

Fifth, the final MRIO table for one year is used as the initial estimate for the following year, and the procedure repeats. This multistep process allows us to construct regionally and sectorally detailed MRIO tables for any given year between 1990 and 2016. To this end, we obtained the balanced MRIO tables tailored to specific datasets for the years 1999, 2009, and 2016. These years correspond to those in which the four natural disaster case studies occurred.

2.1.2. Data sources

Table 1 shows the raw data used for the development of Taiwan's MRIO tables. The 2011 national IO tables obtained from National Statistics of Taiwan are the main source for the construction of the initial estimate (National Statistics, 2017b). A number of data items are used to constrain MRIO elements, namely the 2001 and 2006 national IO tables (National Statistics, 2017b), a set of national accounts from 1990 to 2016 (National Statistics, 2017e), and detailed regional employment data at the city-county level. The latter contain 241 sectors in the Industry and Service Census (National Statistics, 2017d), 20 sectors in the Agriculture, Forestry, Fishery, and Animal Husbandry Census (National Statistics, 2017a), and 6 sectors in the Public Services and Education Census (National Statistics, 2017c).

2.2. Disaster case study of Taiwan

2.2.1. Disaster events in Taiwan

Since 1990, a total of 96 catastrophic earthquakes have occurred in Taiwan, most had their epicentre in open sea off the island's east coast (Central Weather Bureau, 2017a). The Chichi earthquake in Nantou County on 21 September 1999 was the deadliest in modern Taiwanese history. It measured 7.3 on Richter scale with tremors felt across the island and killing at least 2400 people. It caused extensive damages to buildings, public infrastructure, and electricity and water networks. The total damage was estimated at 300 billion New Taiwan Dollars (NT$; 1 US$ $\approx$ 31 NT$) or about 3% of Taiwan's GDP in 1999 (Tsai et al., 2013). After the 1999 Chichi earthquake, the next most deadly earthquake occurred in Tainan on 6 February 2016. It measured 6.4 in moment magnitude, caused 114 casualties, and resulted in NT$ 1 billion in damage (Vervaeck and Daniell, 2016).

Taiwan is also vulnerable to typhoon landings, which bring excessive rainfall and severe flooding. Morakot, the deadliest typhoon to strike Taiwan in modern history, battered the island on 8 August 2009. At least 677 people were killed, 1612 houses were destroyed and financial losses reached NT$ 90 billion (Yang et al., 2014). Despite crossing the central regions, the strong winds and heavy rain accompanying the typhoon triggered a massive landslide and severe flooding throughout southern Taiwan. On 25 September 2016, typhoon Megi made landfall in Hualien County in eastern Taiwan. The 1015 mm of rainfall from typhoon Megi caused NT$ 1 billion in agriculture losses (Hsu-min et al., 2016).

2.2.2. Methods

We use the method proposed by Steenge and Bočkarjova (2007) to study post-disaster consumption possibilities resulting from four selected disasters that hit Taiwan between 1999 and 2016, as described in Section 2.2.1. Roughly speaking, we may divide the literature on disaster analysis within an interindustry setting into three strands. On the one hand, the computable general equilibrium (CGE) approach (see e.g. Okuyama, 2007) allows modelling some behavioural aspects. But such models can take enormous amounts of time and labour to build. On the other hand, IO (see e.g. Okuyama and Santos, 2014) yields simple and somewhat more tractable model that is relatively easy to build. A third is systems econometric time-series models (see West and Lenze, 1994) showing how recovery will likely roll out over time in the case of smaller disasters. But there is no a single 'one size fits all' approach exists. Different (types of) disasters induce different economic behaviour that require different modelling approaches.

For example, within the IO approach, the inoperability model has been widely applied (see Greenberg et al., 2012, for its importance). Recently, however, Dietzenbacher and Miller (2015) noted that this model is at best a mild variation of the supply-side model conceived by Ghosh (1958). In a similar vein, Oosterhaven (2017) points at other shortcomings, including the inability of the inoperability model to handle supply disruptions.

In the present paper, we take supply shocks as our starting point. Instead of building a supply-driven model (Ghosh, 1958) or using nonlinear programming techniques (Oosterhaven and Bouwmeester, 2016), we use a linear programming model in connection with the so-called event matrix as proposed by Steenge and Bočkarjova (2007). In principle, their idea is simple. A disaster or disruption leads to damages and a reduction in production capacity. To this end, Steenge and Bočkarjova (2007) introduce the concept of a so-called event matrix that identifies the reduction in production capacity that results from some event. They assume that capacity if fully employed, which then yields the immediate post-disaster output levels. A consequence can be that the sum of final demands and intermediate inputs (necessary to produce the post-disaster output) are larger than the post-disaster outputs. In other words, total demands are larger than total supply and the economy cannot self-reproduce. They then discuss possibilities for the recovery process.

In our paper, we follow Steenge and Bočkarjova (2007) and assume that production capacity is reduced due to damages from a disaster. But we do *not* assume the production capacity is fully employed[2] as they originally propose. Rather we require that outputs are not larger than the production capacity. Secondly, we do not start from given final demands. Rather we require that the intermediate input demands do not exhaust outputs. That is, the net output, i.e. output that is used to meet final demands, must be nonnegative. These two requirements define a set of feasible solutions (i.e. output levels) from which we select the one that maximises the sum of outputs.[3] That is, we adopt a linear programming approach. After we obtain the optimal post-disaster output levels, we calculate the loss in value-added as an indicator of the impact of a disaster[4]. We focus on a single year of impacts and ignore any dynamics of post-disaster period.

2.2.2.1. Technical details. Steenge and Bočkarjova (2007) require information about reductions in production that can result directly from a disaster, such as damages to public facilities, agriculture, manufacturing sites, and utilities. This information is assembled in the so-called event matrix $\hat{\boldsymbol{\gamma}}$ that quantifies the relative loss in total output by specific region and sector. We follow this approach by defining a diagonal event matrix $\hat{\boldsymbol{\gamma}}$ with elements γ_i, which indicate the share of the output in industry i that is lost. In addition to the event matrix $\hat{\boldsymbol{\gamma}}$, our method requires known the pre-disaster total output vector $\mathbf{x}_0$ and the matrix $\mathbf{A}$ with the economy's production recipe. The outcomes of our method are the post-disaster outputs $\tilde{\mathbf{x}}$ and the net outputs for final demand purposes $\tilde{\mathbf{y}} = (\boldsymbol{I} - \boldsymbol{A})\tilde{\mathbf{x}}$.

We determine the post-disaster output by maximising economy-wide total output $\max\left(\sum \tilde{x}_i\right)$, subject to two conditions. First, $\tilde{\mathbf{x}} \leq (\boldsymbol{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$, where $\mathbf{I}$ is an identity matrix. Our second condition is that post-disaster net outputs are nonnegative, $\tilde{\mathbf{y}} \geq 0$. Since coefficients in $\mathbf{A}$ remain the same as pre-disaster, the economic structure is unchanged. Thus, we assume businesses are unable to recover their original production status through import substitution and factor substitution (capital vs. labour) at least in the short run. The overall linear programming problem becomes $\max\left(\sum \tilde{x}_i\right)$ subject to $\tilde{\mathbf{x}} \leq (\boldsymbol{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$ and $\tilde{\mathbf{y}} = (\boldsymbol{I} - \boldsymbol{A})\tilde{\mathbf{x}} \geq 0$.

To measure the severity of the disaster one usually adopts the loss of capacity. This would be $\mathbf{e}'(\boldsymbol{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0 - \mathbf{e}'\tilde{\mathbf{x}} = \sum_i [(1-\gamma_i)x_{0,i} - \tilde{x}_i]$, where $\mathbf{e}$ indicates the summation vector of ones. In the present study, we use the value-added loss, which is determined by the difference between the post-disaster value-added $\tilde{q}$ and the pre-disaster value-added q_0. In order to estimate the value-added loss $q_0 - \tilde{q}$, we need the vector of value-added coefficients (i.e. value added per unit of output). Let the vector of pre-disaster values-added be given by $\boldsymbol{q}_0$. The vector of value-added coefficients then yields $\mathbf{v} = \hat{\boldsymbol{x}}_0^{-1}\boldsymbol{q}_0$. Vectors are columns by definition, row vectors are transposed column vectors. The estimate for the total post-disaster value-added is $\tilde{q} = \mathbf{v}'\tilde{\mathbf{x}}$ and the loss in value-added yields $q_0 - \tilde{q} = \mathbf{v}'(\mathbf{x}_0 - \tilde{\mathbf{x}})$.

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[2] Oosterhaven and Többen (2017) show in an IO context that full capacity utilisation leads to substantially higher indirect disaster impacts. A similar finding was reported by Hallegatte and Ghil (2008) using a systems time-series macroeconomic model.

[3] In the context of underutilised capacities, excess demand (households can consume less than desired due to the disaster) and prices fixed (as always in the quantity IO model), maximising output implies profit maximisation.

[4] Natural disasters can yield positive impacts to regions or sectors that are not directly affected (cf. Carrera et al., 2015; Koks and Thissen, 2016; Oosterhaven and Többen, 2017).

2.2.2.2. An example of spillover calculation. Take the numerical example in Steenge and Bočkarjova (2007), where the event matrix has been adapted. That is, $\mathbf{A} = \begin{bmatrix} 0.25 & 0.4 \\ 0.14 & 0.12 \end{bmatrix}$, $\mathbf{x}_0 = \begin{bmatrix} 100 \\ 50 \end{bmatrix}$, $\mathbf{y}_0 = \begin{bmatrix} 55 \\ 30 \end{bmatrix}$, and $\mathbf{I} - \hat{\boldsymbol{\gamma}} = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.8 \end{bmatrix}$.

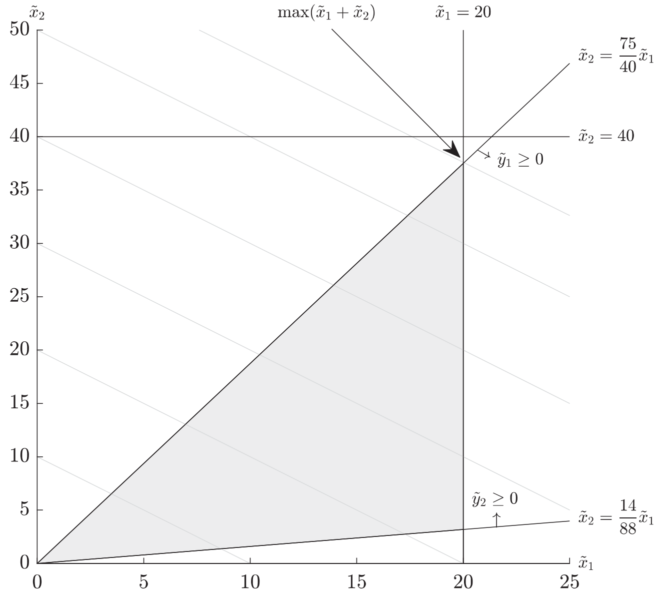
The condition $\tilde{\mathbf{x}} \leq (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$ implies that $\tilde{x}_1 \leq 20$ and $\tilde{x}_2 \leq 40$, and the condition $(\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}} \geq 0$ implies that $0.75\tilde{x}_1 \geq 0.4\tilde{x}_2 \Leftrightarrow \tilde{x}_2 \leq (75/40)\tilde{x}_1$, and $0.14\tilde{x}_1 \leq 0.88\tilde{x}_2 \Leftrightarrow \tilde{x}_2 \geq (14/88)\tilde{x}_1$. In Figure 3, we have the shaded area with feasible solutions. Anything below the line $\tilde{x}_2 = (75/40)\tilde{x}_1$ gives values $\tilde{y}_1 > 0$ and anything above $\tilde{x}_2 = (14/88)\tilde{x}_1$ gives $\tilde{y}_2 > 0$. The solution for maximising total output $\max\left(\sum \tilde{x}_i\right)$, where both $\tilde{\mathbf{x}} \leq (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$ and $\tilde{\mathbf{y}} = (\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}} \geq 0$ is $\tilde{\mathbf{x}} = \begin{bmatrix} 20 \\ 38 \end{bmatrix}$ and $\tilde{\boldsymbol{y}} = \begin{bmatrix} 0 \\ 30.2 \end{bmatrix}$.

Note that the optimal outputs do not absorb the maximum available capacity. If the output levels would equal capacity the net output of industry 1 would become negative. That is, if $\tilde{\mathbf{x}} = (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0 = \begin{bmatrix} 20 \\ 40 \end{bmatrix}$, then $\tilde{\boldsymbol{y}} = (\boldsymbol{I} - \boldsymbol{A})\tilde{\mathbf{x}} = \begin{bmatrix} -1 \\ 32.4 \end{bmatrix}$.

If we set $\mathbf{I} - \hat{\boldsymbol{\gamma}} = \begin{bmatrix} 0.25 & 0 \\ 0 & 1 \end{bmatrix}$, industry 2 does not experience a direct disaster hit. The optimal solution is $\tilde{\mathbf{x}} = \begin{bmatrix} 25 \\ 47 \end{bmatrix}$ and $\tilde{\boldsymbol{y}} = \begin{bmatrix} 0 \\ 37.75 \end{bmatrix}$. Observe that although industry 2 is not affected directly by the disaster, it is in an indirect way. This shows that industry spillovers may occur despite the disaster being restricted to one industry. If a multiregional model is used, this finding extends to regional spillovers.

2.2.2.3. Alternative objective functions. In the example above and in the empirical application in Section 3, we maximise the sum of the gross outputs. It should be stressed though that our linear programming approach is very flexible and allows for many alternative objective functions. As the term indicates, the function one chooses depends on one's objective. It may reflect economic behaviour or the goals of policy-makers, it may also be normative and based on political viewpoints.

Figure 3. Feasible solution space for $\tilde{\mathrm{x}} \leq (\mathrm{I} - \hat{\boldsymbol{\gamma}})\mathrm{x}_0$ and $\tilde{\boldsymbol{y}} = (\boldsymbol{I} - \boldsymbol{A})\tilde{\mathrm{x}} \geq 0$, for the example in Section 2.2.2.2.



In what follows, we describe several examples of alternative objective functions. The objective function depends on the question(s) one would like to answer and should be chosen very carefully. Therefore, we illustrate some of the more plausible and more common objective functions. First, the aim might be to keep the post-disaster outputs closest to the pre-disaster outputs. The objective function then becomes $Z = \sum_i (\tilde{x}_i - x_{0,i})^2$. The optimisation problem is to find the values $\tilde{x}_i$ that minimise Z, subject to the constraints.

Second, Oosterhaven and Bouwmeester (2016, p. 586) 'simulate the *back to business-as-usual* behaviour of economic actors ... [and] minimise the difference in the information value of the post-event compared to the pre-event market equilibrium as measured by the ... input-output table'. As an alternative, one may consider firms that try to stick to their pre-disaster business patterns as close as possible. This might be modelled by requiring that the new outputs are proportional to the original outputs. This implies an additional set of constraints, i.e. $\tilde{x}_i = \lambda x_{0,i} \forall i$. The optimisation problem then would be to find the maximum value of λ, subject to the constraints.

Third, the objective function might be defined in terms of the consumption possibilities $\tilde{y}_i$. Recall that the model is such that the output levels are chosen (or given) exogenously. This means that also the intermediate inputs $\mathbf{A}\tilde{\mathbf{x}}$ – that producers need – are predetermined for any given $\tilde{\mathbf{x}}$. Post-disaster final demand is then determined endogenously as the residual, i.e. $\tilde{\mathbf{y}} = (\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}}$; it is what is left of the outputs after the intermediate deliveries have been satisfied. These leftovers are to satisfy consumption. We may choose to maximise total consumption ($\sum_i \tilde{y}_i$) or we may attach weights to the consumption of separate goods. Natural disasters destroy homes, agriculture, and business assets. At the same time, people require basic goods (like food, clothing, housing) to survive. Therefore, we might give basic goods large weights and luxury goods (like cars or travelling for touristic purposes) small weights. In that case, the objective function becomes $Z = \sum_i w_i \tilde{y}_i$, which can be rewritten as $Z = \sum_i \mu_i \tilde{x}_i$ with $\mu_i = w_i - \sum_j w_j a_{ji}$.

Fourth, the measure for the severity of the disaster might be adopted as the objective function. If the loss of capacity is used, we might use as the objective to minimise this loss. That is, minimise $Z = \sum_i [(1 - \gamma_i) x_{0,i} - \tilde{x}_i]$, which can be rewritten as maximise $Z = \sum_i \tilde{x}_i$. Note that this is exactly the same as the objective function that we are currently using. If the value-added loss is chosen as the evaluation criterion, we might use to minimise that measure. That is, minimise $Z = \sum_i v_i (x_{0,i} - \tilde{x}_i)$, which is the same as maximise $Z = \sum_i v_i \tilde{x}_i$.

2.2.2.4. Event matrix $\hat{\gamma}$. In order to populate the event matrix $\hat{\gamma}$ for the four disasters, we use the information on financial damages from public sources such as government and NGO reports, academic journal articles, and government statements in online media. To give an example, in the case of the 1999 Chichi Earthquake, the information of the direct losses includes:

- electric power outages lasted for 1–2 weeks mostly in central and northern Taiwan and caused severe business interruptions (Chang, 2000);
- farmers in central Taiwan experienced significant losses in their facilities, and the reconstruction costs were estimated at NT$ 26.2 billion (Low, 1999);
- tourism lost revenue worth NT$ 1 billion (Chuang, 1999);

- transportation and communications infrastructure needed repairs valued at NT$ 10 billion across all areas (Chang, 2000); and
- general damages to communities, estimated using the post-disaster reconstruction funds (e.g. public and community reconstruction), costed NT$ 212.4 billion to the Taiwan government budget (Tsai et al., 2013).

Some of the above information was not available by region, but instead as a total only. We dealt with such circumstances as follows. In the absence of detailed information about economic impacts in specific regions, we used data on the region-specific damages to buildings (Tsai et al., 2000) to disaggregate the direct economic effects of the earthquake to all cities and counties. In addition, we used data on the length of city-county highways to allocate total damages to regions as incurred by the transportation and communication sectors.

It is less straightforward to estimate the production shortfalls, which might arise due to damaged infrastructure. The input of fixed capital (*FC*) – in form of depreciation – into production is part of value-added. *FC* is often – most certainly so in Taiwan – lumped together with Gross Operating Surplus (*GOS*). Since $FC \leq GOS$, the ratio $g_i = x_i/GOS_i \leq x_i/FC_i$ provides a lower limit for the industrial output of sector i enabled by the annual input of fixed capital. To estimate the reduction in sectoral total output due to infrastructure damages, we utilise an approach outlined in Lenzen et al. (2019). Here, we follow Hallegatte (2008) in assuming that a) the infrastructure loss is equivalent to a loss of fixed capital inputs, annualised over a 25-year time-frame, and that b) the reduced output of the damaged industries is approximated by the value of this loss multiplied by the output-enabling ratio g_i. Thus, we arrive at a lower limit – i.e. a conservative estimate – for the production shortfalls due to damaged infrastructure, which we enter as a separate component of the event matrix $\hat{\boldsymbol{y}}$ for capital losses (representing around 20% of total losses for the four disasters investigated). An event matrix $\hat{\boldsymbol{y}}$ containing both direct and capital damage components is shown for the 1999 Chichi Earthquake for 22 regions and 9 sectors in Table 2. We apply the aforementioned methods to construct the event matrices $\hat{\boldsymbol{y}}$ for other natural disaster covered in this paper, including the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi (see Appendix 6).

2.2.2.5. Production-layer decomposition.

Production-layer decomposition analysis (Lenzen et al., 2019) is then performed to decompose losses in value-added across upstream layers of production resulting from the case studies. Recall that we have defined $\tilde{\mathbf{y}} = (\boldsymbol{I} - \boldsymbol{A})\tilde{\mathbf{x}}$. This implies $\tilde{\mathbf{x}} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\tilde{\mathbf{y}} = \mathbf{L}\tilde{\mathbf{y}}$. We can do the same for the pre-disaster values. That is, $\mathbf{y}_0 = (\boldsymbol{I} - \boldsymbol{A})\mathbf{x}_0$ or $\mathbf{x}_0 = \mathbf{L}\mathbf{y}_0$. The production-layer decomposition is determined by $q_0 - \tilde{q} = \mathbf{v}'(\mathbf{x}_0 - \tilde{\mathbf{x}}) = \mathbf{v}'\mathbf{L}(\mathbf{y}_0 - \tilde{\mathbf{y}}) = \mathbf{v}'(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \ldots)(\mathbf{y}_0 - \tilde{\mathbf{y}})$. Here, $(\mathbf{y}_0 - \tilde{\mathbf{y}})$ is the reduction in consumption possibilities (Steenge and Bočkarjova, 2007). Specifically, we quantify value-added losses broken down by sectors and by regions of the upstream supply chain. Upstream production-layers are shown on the x-axis, with 0 representing the value-added loss in sectors affected immediately by the reduction of consumption possibilities $(\mathbf{y}_0 - \tilde{\mathbf{y}})$, 1 being the value-added loss experienced by the suppliers of sectors in layer 0, and so on.

Table 2. Event matrix $\hat{y}$ for the 1999 Chichi Earthquake.

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	0.0099	–	–	0.0241	–	0.0001	0.0016	–	0.0002
Taoyuan	0.0038	–	–	0.0230	–	0.0000	0.0002	–	0.0000
Yilan	–	–	–	–	–	–	–	–	–
Hsinchu City	0.0880	–	–	0.0335	–	0.0001	0.0004	–	0.0002
Keelung	–	–	–	–	–	–	–	–	–
New Taipei	0.2361	–	–	0.0296	–	0.0002	0.0029	–	0.0006
Taipei	0.0786	–	–	0.0324	–	0.0000	0.0000	–	0.0002
Changhua	0.0153	–	–	0.0248	–	0.0003	0.0235	–	0.0007
Miaoli	0.0942	–	–	0.0313	–	0.0022	0.0482	–	0.0031
Nantou	0.6154	–	–	0.0310	–	0.0270	0.4047	–	0.0400
Yunlin	0.0153	–	–	0.0326	–	0.0008	0.0330	–	0.0011
Taichung	0.3762	–	–	0.0305	–	0.0020	0.0280	–	0.0053
Chiayi County	0.0007	–	–	0.0245	–	0.0001	0.0034	–	0.0001
Penghu	–	–	–	–	–	–	–	–	–
Pingtung	–	–	–	–	–	–	–	–	–
Chiayi City	0.0035	–	–	0.0302	–	0.0000	0.0001	–	0.0000
Kaohsiung	–	–	–	–	–	–	–	–	–
Tainan	–	–	–	–	–	–	–	–	–
Hualien	–	–	–	–	–	–	–	–	–
Taitung	–	–	–	–	–	–	–	–	–
Kinmen	–	–	–	–	–	–	–	–	–
Lienchiang	–	–	–	–	–	–	–	–	–

Notes: It is possible some manufacturing firms also directly experienced facility damages, however, we do not include any losses for the manufacturing sectors since these stems mostly from electric power outages, which we already capture in our supply-chain calculus. For sector names see Appendix 2.

3. Results

Before delving into the description of the results for our disaster impact assessment, we should briefly describe the multiregional economic features that emerge from our Taiwan MRIO database. This description should aid in understanding the characteristics and significance of the distribution of regional disaster impacts and their relationships with Taiwan's economic geography. Therefore, we first present Taiwan's economic structure as represented by the TaiwanLab's MRIO, and then refer to these features when describing the regional and sectoral impacts – including spillovers – of the four disasters.

3.1. Taiwan's economic structure

The TaiwanLab has built-in data repositories and tools for constructing a time-series of MRIO tables for the Taiwan economy from 1990–2016, distinguishing up to 267 industry sectors for 22 city-counties. The tables are valued in millions of NT$. To demonstrate the capability of virtual laboratories for disaster analysis, we use the TaiwanLab to construct MRIO tables for years 1999, 2009, and 2016, which correspond to the years of our natural disaster case studies. For the sake of conciseness in presenting our findings only, we aggregate the 267 industry sectors represented in the MRIO tables into 9 broad categories: agriculture (including livestock, forestry, and fishery); mining and quarrying; manufacturing; utilities; construction; trade, hotels and restaurants; transportation and communication; financial services (including real estate, and business services); and other services.

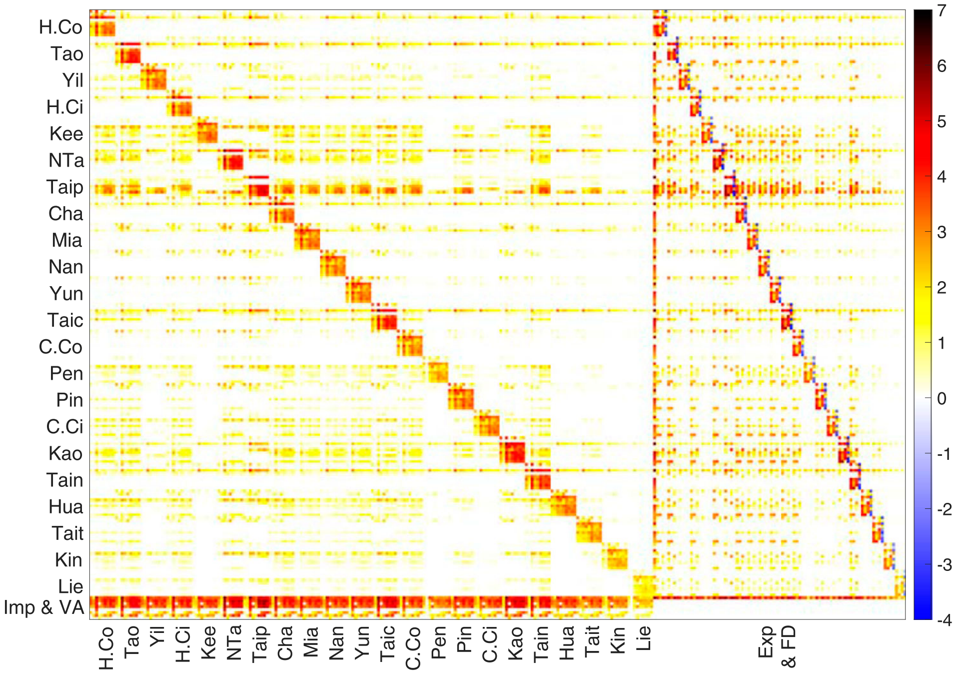
Table 3. Taiwan's regional output for the year 2016 (in NT$ billion).

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	22.2	2.2	659.1	12.0	36.0	91.6	34.2	75.3	80.4
Taoyuan	18.1	0.6	2461.5	33.1	119.3	394.1	195.7	305.5	172.6
Yilan	19.0	1.4	203.2	32.6	38.3	70.5	25.4	42.4	86.7
Hsinchu City	8.3	0.9	761.7	17.5	41.9	108.8	37.6	113.8	89.6
Keelung	2.3	0.6	93.1	73.8	23.2	46.4	59.3	29.3	76.7
New Taipei	12.7	0.4	2759.6	41.5	280.5	708.1	279.1	515.3	437.1
Taipei	6.5	0.9	1360.6	63.5	85.9	1130.8	765.3	1714.2	872.8
Changhua	65.8	0.6	1145.1	14.4	36.6	184.3	47.7	106.0	174.6
Miaoli	29.0	6.7	424.2	34.4	35.0	77.1	27.8	57.2	85.5
Nantou	40.0	1.4	236.2	42.1	27.5	71.9	21.9	39.3	89.5
Yunlin	57.2	0.6	381.9	52.4	39.3	89.3	30.7	50.7	99.9
Taichung	57.2	1.0	2499.3	39.7	186.3	581.8	173.6	441.2	508.1
Chiayi County	43.7	0.4	290.8	12.4	28.5	62.6	19.8	37.5	79.6
Penghu	2.3	0.0	13.3	27.1	6.7	12.9	8.0	7.6	19.4
Pingtung	54.0	2.0	274.8	62.6	40.8	117.5	27.8	58.4	144.9
Chiayi City	4.6	0.4	80.7	33.5	14.6	54.3	16.0	39.0	76.4
Kaohsiung	67.3	0.7	1765.0	184.4	233.7	526.6	238.7	435.6	543.7
Tainan	70.8	0.6	1780.4	28.0	31.4	324.8	84.9	231.3	311.8
Hualien	14.5	2.6	85.6	54.9	23.4	55.1	23.8	31.7	78.8
Taitung	13.4	1.6	37.7	17.0	11.5	33.5	10.4	15.9	49.2
Kinmen	1.7	0.1	19.2	32.8	7.2	9.5	6.9	6.2	11.1
Lienchiang	0.1	0.0	2.3	4.2	1.9	1.4	1.9	1.0	2.8

Table 3 shows detailed outputs of 9 economic sectors in 22 Taiwan's city-counties. The leading manufacturing hubs are mainly Taoyuan (16% of the national total), New Taipei (14%), Taichung (14%), Tainan (10%), and Kaohsiung (10%), while agricultural output mainly stems from Tainan (12%), Kaohsiung (11%), Changhua (11%), Yunlin (9%), and Taichung (9%). Taipei is the core of the nation's economy. Along with New Taipei (formerly Taipei County) and Taoyuan, Taipei has become the primary host for national financial services, and transportation and communication sectors with a combined output of more than 60% of the island's total output. Taipei also produces significant outputs in trade, hotel, and restaurant sectors, and other services, representing a national share of 24% and 21%, respectively. Northern Taiwan's regions (Taipei, New Taipei, Taoyuan, Keelung, Hsinchu, and Miaoli) maintain 50% of the national manufacturing. It is the island's main home for high-tech manufacturing such as electronic components, computer and optical products, and electrical equipment, which is facilitated by the presence of science parks and easy access to international ports.

Central and southern Taiwan each contribute around 20% of Taiwan's total economic activity. These regions produce a range of commodities: For example, city-counties in central Taiwan (Taichung, Changhua, Nantou, and Yunlin) are the main producers of leather, rubber, wood, and furniture. Regions in southern Taiwan (Chiayi, Tainan, Kaohsiung, and Pingtung) and also the aforementioned central regions are the main hubs for agriculture, livestock, forestry, and fishery products. Producing two-thirds of Taiwan's agricultural output, city-counties in central and southern Taiwan have comparative advantages in agriculture-related manufactured products, such as food and beverage manufacturing. The central and southern regions have also significant mining-related industries such as petroleum refineries, and basic metal manufacturing. The eastern regions of Yilan, Hualien, and Taitung and the offshore regions of Penghu, Kinmen, and Lienchiang contribute less than 4% to Taiwan's economic activities.

Figure 4. Heat map of the 2016 Taiwan MRIO table.



Note: The diagonal blocks of the intermediate demand and the final demand matrices show intra-regional trade within the 22 city-counties; the off-diagonal blocks represent interregional trade between different regions; and the blocks below the intermediate demand matrix are the imports and the value-added matrices. Exports of goods and services are placed in a vertical column to the right of the intermediate demand matrix. The cell colours indicate the magnitude of the trade transactions on a log-scale. The Taiwan MRIO tables are valued in NT$1 million, hence the colour tone against a value of 2 represents a transaction of NT$100 m. Imp = Import, VA = Value-Added, Exp = Export, and FD = Final Demand. For sector, FD, and VA names see Appendix 3.

In Figure 4, we display a heat map of the 2016 Taiwan MRIO table. The heat map allows for a visual assessment of Taiwan's inter-regional supply-chain structure. For example, the dark row of matrices for Taipei indicate a high dependence of the other regions on Taipei. The row of matrices of city-counties in northern Taiwan – Taipei (Taip), New Taipei (NTa), Taoyuan (Tao), and Keelung (Kee) – show relatively large interregional trade flows, again indicating how much the rest of Taiwan depends on this region.

3.2. Regional impact of natural disasters

The IO structure and data shown in Table 3 and Figure 4 clearly demonstrate that Taiwan's economy is highly diversified and interconnected. In the following description of the regional and sectoral impacts of the four disasters, we will refer to Table 3 and Figure 4 to highlight regional and sectoral spillover effects. Such spillovers occur, for example, when a natural disaster occurs in a region with a high concentration of agricultural output and, facilitated by interregional supply chains, the economic impact spreads to other regions that depend on agricultural products as their inputs.

3.2.1. *Total output losses*

The literature on economic losses resulting from the four natural disasters in Taiwan that we examine does not mention any regional and sectoral spillover effects (Hsu et al., 2013). Spillover effects occur when sectors and regions, which do not experience any direct effects of the disaster, are negatively affected by supply chain interruptions. In particular, these reports only document the direct impacts, i.e. impacts in directly affected regions. Reports by the Taiwan's Directorate General of Budget, Accounting and Statistics (Lin, 1999) and the Risk Management Solutions (Dong et al., 2000), for example, estimated the economic loss of the 1999 Chichi earthquake to be NT$ 290–380 billion. But these reports provided no information about the economic spillover effects, whereas we suggest the 1999 Chichi earthquake caused a total loss on the order of NT$ 508.3 billion (including an indirect loss due to the upstream spillover effects of NT$ 177.7 billion). These total losses result directly out of our maximisation of post-disaster total output $\tilde{\mathbf{x}} \leq (\boldsymbol{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$. By comparing $\tilde{\mathbf{x}}$ and $\mathbf{x}_0$, we can already identify the significance of regional spillovers. However, in the following we will concentrate on our measure $\mathbf{v}'(\boldsymbol{x}_0 - \tilde{\boldsymbol{x}})$ of value-added loss.

3.2.2. *Value-added losses*

The 1999 Chichi earthquake resulted in the loss of NT$ 508.3 billion of value-added, 40% of which occurred as sectoral and regional spillovers. Initially, the earthquake damaged transportation links and the power plants, particularly around Taichung which is close to the earthquake's epicentre. The electricity outages affected the operation of many businesses nation-wide, and consequently, manufacturing and trade sectors encountered a total loss of NT$ 159.5 billion and NT$ 123.2 billion, respectively. Almost half of the losses in both sectors were felt in Taipei, New Taipei, Taoyuan, and Hsinchu, despite the distance of these city-counties from the earthquake's epicentre, because of the grid-wide effects of power generation and transmission outages. Our MRIO-based analysis shows that the loss of the northern manufacturing sectors, especially those producing computers, electronic equipment, and motor vehicles, reduced interregional demand from Taichung's machinery, Tainan's basic metal, and Kaohsiung's chemical products. As a result, Taichung and the southern regions of Kaohsiung and Tainan also experienced significant spillover loss in the manufacturing sectors (worth NT$ 58.3 billion) and the trade sectors (worth NT$ 38.3 billion).

The spillover effects from the damage of transportation links also triggered a drastic reduction in the output of manufacturing and the trade sectors in the north. Based on the MRIO structure, spillovers due to transportation and communication losses, such as in airports, seaports, and telephone networks, amounted to NT$ 38.3 billion. Approximately two-thirds of these losses were felt in New Taipei and other northern manufacturing hubs. In this case, extensive damages to roads and bridges throughout Nantou, Taichung, Chiayi, and Yunlin, and the railway tracks near Taichung (Dong et al., 2000) cut access to the north for several weeks. This affected the freight delivery of critical inputs from Taoyuan and New Taipei's manufacturing sectors to their central and southern customers, and vice versa.

The financial, real estate, and business services sectors suffered substantial losses of NT$ 95.4 billion following the week-long closure of the Taiwan Stock Exchange, the increase of property insurance claims to NT$ 15.4 billion, and the payment reschedule of the mortgage debts (Chang, 2000). Most of the insurance claims and the bad credits occurred in

Nantou, Yunlin, Changhua, Taichung, and Tainan. However, Taipei and New Taipei carried most of the spillover effect in the financial sectors (worth NT$ 53.4 billion) because these cities are the centre of the financial, real estate, and business services activities in Taiwan.

The 1999 Chichi earthquake caused serious damage to public facilities such as schools and hospitals. The total loss in public services was valued at NT$ 62 billion, and the effects were felt across all regions. In particular, city-counties with a high seismicity experienced higher loss than other city-counties.

The loss in agriculture, livestock, forestry, and fishery sectors was equivalent to NT$ 11 billion, 60% of which was felt in the central regions of Changhua, Yunlin, Taichung, and Nantou, where the earthquake's epicentre was located. Since these cities and counties supplied around 40% of the Taiwan's agricultural outputs (see Table 3), the losses borne by these regions spread to the downstream food and beverage factories in Taoyuan, New Taipei, and Tainan, which in turn reduced the (semi-)processed food products supply to restaurants in Taipei. Based on our MRIO database, the restaurant sectors in Taipei suffered a value-added loss of NT$ 2 billion.

The 2009 typhoon Morakot resulted in a value-added loss of NT$ 71.9 billion. As the typhoon triggered extreme flooding in the south, the majority of the losses (about 60%) were felt in city-counties throughout southern Taiwan. Tainan experienced the largest loss of all regions, approximately NT$ 13.4 billion, mostly in the agriculture, livestock, forestry, and fishery sectors. Based on our MRIO data, Tainan's agricultural damages reduced the supply of raw agricultural products to Taoyuan and New Taipei's food and beverage industries, leading to a value-added loss of NT$ 5.1 billion. The extreme flooding also caused a combined loss of NT$ 13.6 to the agricultural sectors in southern regions of Pingtung, Kaohsiung, and Chiayi, and central regions of Nantou, Taichung, and Yunlin. This in turn affected the sizable agriculture-related manufacturing in all city-counties in central and southern Taiwan: our results show that the typhoon caused an indirect loss of about NT$ 6.9 billion in the manufacturing sectors of these regions.

Typhoon Morakot resulted in a combined loss of NT$ 18.5 billion for trade, hotel, and restaurants, transportation and communication, and other services. Typhoon-triggered damage to public facilities reduced tourism activities, passenger delivery, and education services in Tainan, Kaohsiung, Pingtung, and Chiayi. As manufacturing activities, such as supply delivery from Chiayi to Taoyuan, were also disrupted, the damage on public infrastructures spilled over to the manufacturing sectors in Taoyuan and New Taipei. In addition, the typhoon indirectly hit Taipei's financial, real estate, and business services with a loss worth NT$ 2.2 billion. This indirect loss mainly resulted from the spillover effects of the increase in the insurance claims in Tainan, Chiayi, Pingtung, and Kaohsiung.

In the case of the 2016 Tainan earthquake, the value-added loss was about NT$ 1.9 billion. Since the epicentre of the earthquake was in the south, the southern city-counties suffered approximately 80% of the total value-added losses. Most of the losses were felt by education and recreation services sectors due to damages on local schools and tourism monuments, and agricultural sectors due to damages on farming and livestock facilities. In contrast to the 1999 Chichi earthquake, the spillover effects of the 2016 Tainan earthquake were relatively small since the earthquake caused no damage to essential business facilities. While no structural damages were found on the national railway (Shu-Fen and

Liu, 2015), the manufacturing activities in the high-tech factories in the Southern Taiwan Science Park remained normal after the earthquake (Ya-Chen and Hsu, 2015).

The value-added loss resulting from the 2016 typhoon Megi amounted to NT$ 2.5 billion, about 40% of which was felt in agriculture, livestock, forestry, and fishery sectors. Yunlin and Taichung were the hardest-hit regions as the typhoon passed through these city-counties. The shortage of agricultural products from Yunlin, Taichung, Kaohsiung, Tainan, and Yilan triggered a loss in the agriculture-related manufacturing sectors in Taoyuan, and New Taipei, which our MRIO data allow estimating at about NT$ 0.2 billion. Similarly, Typhoon Megi also caused flooding in the south, in turn damaging farm fields, public infrastructures and business sites, and resulting in an indirect loss of NT$ 0.2 billion in Kaohsiung and Tainan's manufacturing sectors. In Figure 5, we show the magnitude of the value-added losses resulting from the 1999 Chichi earthquake, the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi.

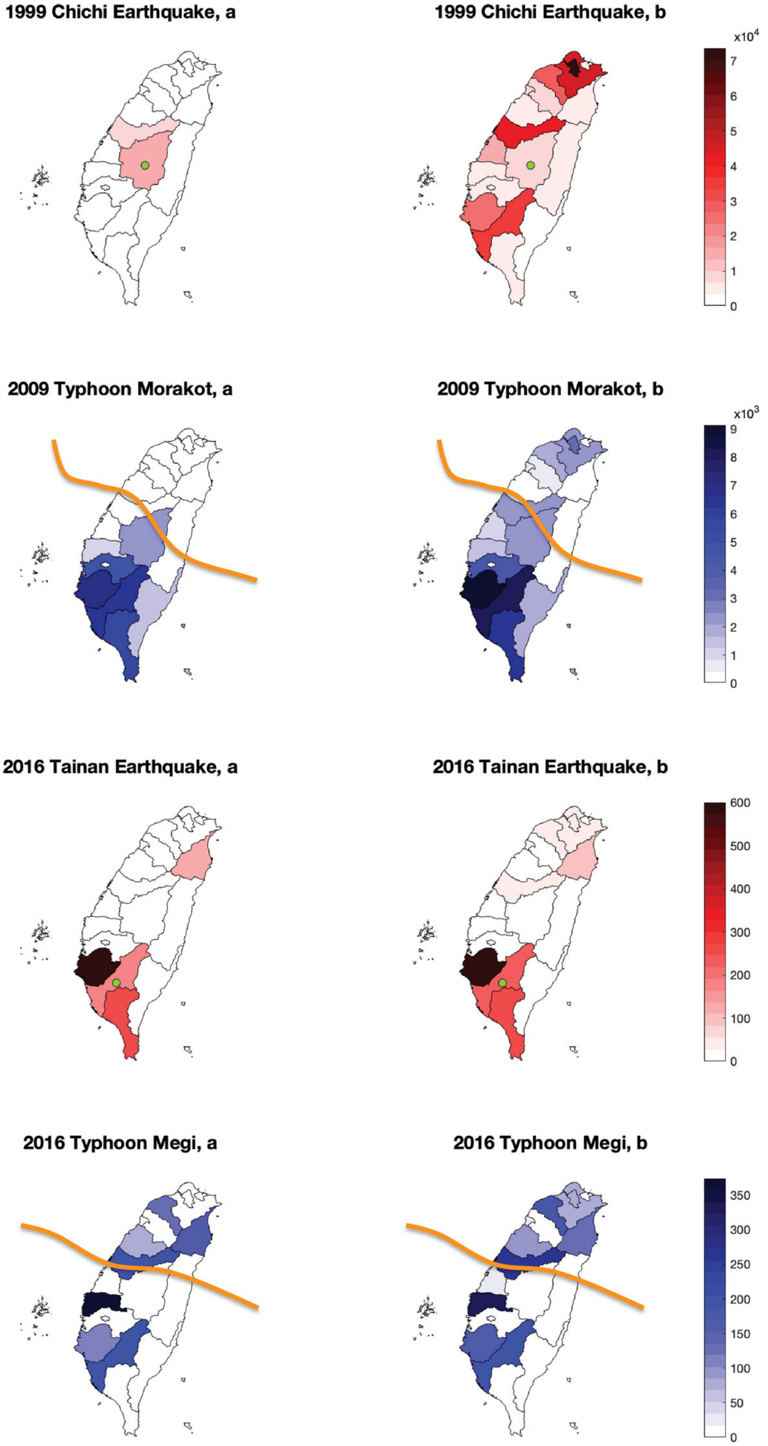
3.2.3. Production-layer decomposition of value-added losses

In what follows we present detailed results for the value-added losses resulting from 1999 Chichi Earthquake, particularly, since this disaster was the most destructive of the four selected natural disasters. Results from the production-layer decomposition analysis reveal that the 1999 Chichi earthquake resulted in NT$ 177.6 billion loss in value-added in the upstream supply-chain, in addition to NT$ 330.4 billion value-added losses. The manufacturing sectors, the trade, hotel, and restaurant, the financial services, and the transportation and communication had the biggest fraction of this upstream supply-chain effect, equal to NT$ 75.7 billion, NT$ 42.8 billion, NT$ 30.5 billion and NT$ 14.3 billion loss, respectively (Figure 6, left panel). Meanwhile, the northern regions of Taipei, New Taipei, and Taoyuan suffered high regional upstream supply-chain effect worth NT$ 32.9 billion, NT$ 26.9 billion, NT$ 21.4 billion, respectively (Figure 6, right panel). Such upstream supply-chain effects are inevitable in the event of a disaster, since a likely shut-down of one particular business results affects other establishments that depend on its outputs, or that supply its inputs. As a result, the output of these dependent establishments will also be reduced. The MRIO tables depict this inter-relationship between sectors across multiple regions, and therefore serve as a comprehensive analytical tool for disaster assessments.

In the case of the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi, a further value-added loss in the supply-chain was worth NT$ 25.4 billion, NT$ 0.5 billion, and NT$ 0.9 billion, respectively. As manufacturing and trade involved relatively high supply-chain activities, approximately two-thirds of the value-added loss occurred in these sectors.

In Table 4, we summarise the results of value-added losses of each natural disaster in this study. The upstream supply-chain effect is approximately half of the magnitude of value-added losses, leading to a multiplier of 1.4 ∼ 1.5. This means that for each NT$ of value-added directly lost due to reduced consumption possibilities in the wake of a natural disaster earthquake or typhoon in Taiwan, a loss of 0.4 ∼ 0.5 NT$ in value added should be expected due to regional and sectoral spillovers. The Taiwan impact multipliers are slightly below the global multipliers (Okuyama and Sahin, 2009), which range from 1.8 to 2.0 depending on the type of natural disasters: meteorological 2.0, geophysical 1.9, hydrological 1.8, and climatological 1.8.

Figure 5. Regional value-added losses (direct plus spillovers) from four natural disasters in Taiwan.



1999 Chichi Earthquake, a

1999 Chichi Earthquake, b

2009 Typhoon Morakot, a

2009 Typhoon Morakot, b

2016 Tainan Earthquake, a

2016 Tainan Earthquake, b

2016 Typhoon Megi, a

2016 Typhoon Megi, b

Notes: 'a' and 'b' refer to direct and indirect losses, respectively. The dots represent the earthquakes' epicentres, and the lines represent the typhoon paths. The Taiwan MRIO tables are valued in NT$ 1 million, hence a value of 600 in the legend represents a value-added loss of NT$ 600 million.

Figure 6. Cumulative value-added loss resulting from the 1999 Chichi Earthquake (in NT$ billion).

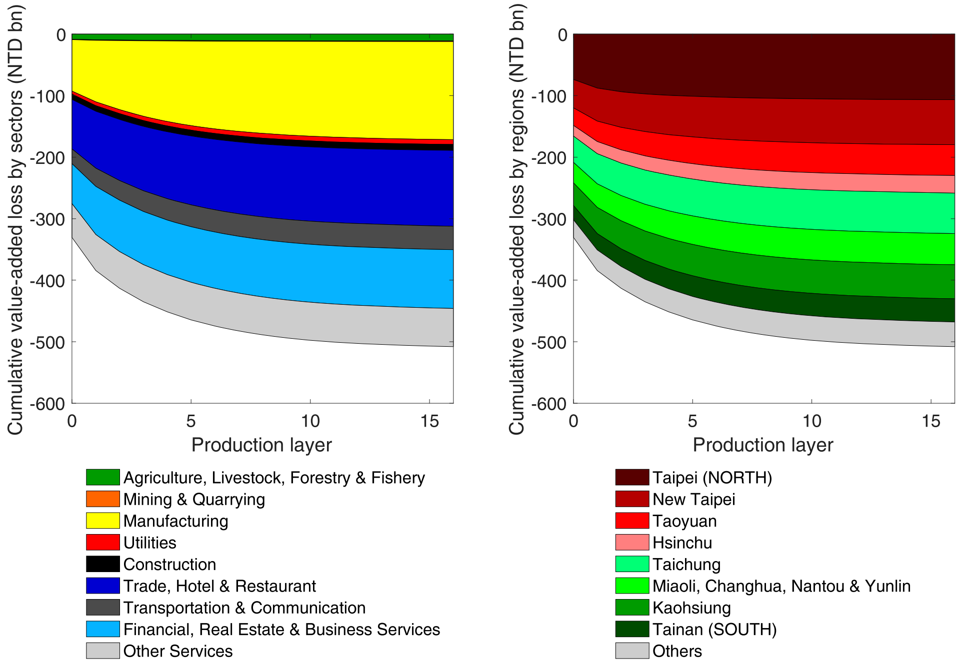


Table 4. Estimation of value-added losses.

	1999 Chichi earthquake	2009 typhoon Morakot	2016 Tainan earthquake	2016 typhoon Megi
Total loss (NT$ billion)	508.0	71.9	1.9	2.5
a) Directly losses as a result of reduced consumption possibilities	330.4	46.5	1.4	1.6
b) Indirect supply-chain losses resulting from a)	177.6	25.4	0.5	0.9
Main sector affected	Manufacturing	Agriculture	Services	Agriculture
Main region affected	Taipei City	Tainan City	Tainan City	Yunlin County

4. Discussion

In this study, we reveal economic impacts of four selected natural disasters in Taiwan, in particular resulting from business and public facility damages, as well as supply-chain interruptions – two areas that researchers have found difficult to model in the case of Taiwan (Hsu et al., 2013). We assess the new TaiwanLab, a collaborative virtual laboratory that is able to generate a time-series of subnational MRIO tables so analysts can capture interregional transactions between 267 economic sectors across Taiwan's 22 city-counties.

The Taiwan MRIO database appears to be able to enable comprehensive disaster impact assessments. By yielding an understanding of the regional economic income distribution, sectoral contributions, and interregional trade flows, the Taiwan MRIO database provides a comprehensive picture of Taiwan's regional economic structure, and how the interconnections within it expose different parts of the nation to natural disasters differentially. Using the Taiwan MRIO database, we identify critical economic sectors in regions with high vulnerability to natural disasters. The analysis could not have been achieved without subnational MRIO tables, and these can be tailored to disaster-analysis-specific questions using a virtual lab.

We subsequently estimate that the 1999 Chichi earthquake, the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi caused a total value-added loss of NT$ 508.0 billion, NT$ 71.9 billion, NT$ 1.9 billion, and NT$ 2.5 billion, respectively. In particular, the losses that resulted from upstream linkages were large, amounting to about half of value-added lost. Since Taiwan's economy is highly interconnected, no single region is unaffected by such disasters. In some cases, a region located far from the disaster's epicentre or path suffered important economic losses. Taipei's and New Taipei's powerful financial and trade sectors, for example, experienced a relatively high value-added loss due to the repercussions of disaster damage in other regions, making these sectors vulnerable regardless of their physical distance from the natural disasters. We also find regional economic impact multipliers of the four natural disasters in Taiwan range between 1.2 and 2.0 (Table 5). These multipliers are the ratio of total impacts $\sum_{n=0}^{\infty} \boldsymbol{v}'(\boldsymbol{I}+\boldsymbol{A}^n)(\boldsymbol{y}_0-\tilde{\boldsymbol{y}})$ to direct losses caused by reduced consumption possibilities $q_0 - \tilde{q}$. The financial and industrial centre of Taipei, New Taipei, and Taoyuan has higher multiplier than do agricultural locations of Yilan, Yunlin, and Nantou. This confirms the work of Kellenberg and Mobarak (2008), who indicates that higher-income regions are more vulnerable to natural disasters than are middle- and lower-income regions. The range of regional multipliers could not have been captured without considering the economic interdependence of the affected areas, as offered by the Taiwan MRIO tables.

In addition, an MRIO-based disaster framework can serve as an early-warning and resilience planning system for regions likely affected by natural disasters. Our analysis of the 1999 Chichi earthquake shows that a relatively small disruption of a vital industrial

Table 5. Regional impact multiplier.

	1999 Chichi Earthquake	2009 Typhoon Morakot	2016 Tainan Earthquake	2016 Typhoon Megi
Hsinchu County	1.6	2.0	1.9	1.9
Taoyuan	1.7	2.0	2.0	1.6
Yilan	1.4	1.9	1.3	1.3
Hsinchu City	1.7	2.0	1.9	1.9
Keelung	1.5	2.0	1.9	1.9
New Taipei	1.6	2.0	2.0	2.0
Taipei	1.4	2.0	2.0	2.0
Changhua	1.6	2.0	2.0	2.0
Miaoli	1.6	1.9	1.9	1.4
Nantou	1.3	1.4	1.9	1.9
Yunlin	1.5	1.4	1.9	1.3
Taichung	1.5	1.9	2.0	1.5
Chiayi County	1.5	1.3	1.9	1.9
Penghu	1.4	1.7	1.8	1.7
Pingtung	1.4	1.3	1.1	1.9
Chiayi City	1.4	1.9	1.9	1.9
Kaohsiung	1.5	1.4	1.4	1.5
Tainan	1.6	1.5	1.2	1.5
Hualien	1.4	1.9	1.9	1.9
Taitung	1.3	1.3	1.7	1.8
Kinmen	1.5	1.8	1.8	1.8
Lienchiang	1.3	1.4	1.5	1.2
National	1.5	1.5	1.4	1.5

input, such as electricity, can cause significant economic losses. Such insight can help governments evaluate the national electric grid, and perhaps suggest the construction of power plants or the storage of back-up transformers nearer essential economic locations, such as high-tech manufacturing and financial markets. Similarly, to ensure the seamless distribution of goods and services, transportation networks connecting west Taiwan could be re-designed to assure more resilience near emergency facilities and important industrial complexes.

5. Conclusions

Disasters are highly localised. Even in a relatively small country like Taiwan, small breaks in supply chains can cause major economywide losses. Therefore, regionally and sectorally detailed multiregional input–output (MRIO) databases are needed to undertake disaster analysis at sufficient resolution. Since disasters can affect agriculture in one region and manufacturing industries in another region, either at the same time or at different times, flexible, adaptive MRIO databases can be quite beneficial. For this reason, we chose to establish a virtual laboratory for Taiwan, the TaiwanLab.

The TaiwanLab provides flexibility to users so they can obtain customised regional and sectoral classifications for MRIO tables, and incorporate a wide variety of primary data. The lab also can update or add additional data to suit specific research questions, so that it allows a wide range of international users to undertake IO modelling on various economic, social, and environmental topics.

Whilst this paper demonstrates the TaiwanLab as a case study for disaster analysis, this innovation can be and is being transferred to other countries such as Australia (Lenzen et al., 2014, 2017), Indonesia (Faturay et al., 2017), China (Wang et al., 2015; Wang, 2017), Japan (Wakiyama et al., 2019), Sweden (Faturay et al., 2019a), and the USA (Faturay et al., 2019b). The hope is for the virtual lab technology to become a blueprint for aforementioned countries to assess the regional economic impacts of natural disasters.

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