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ABSTRACT

Disasters often cause exogenous flow damage (i.e., the [hypothetical] difference in economic scale with and without a disaster in a certain period) to production ("supply constraint"). However, input-output (IO) analysis (IOA) cannot usually consider it, because the Leontief quantity model (LQM) assumes that production is endogenous; the Ghosh quantity model (GQM) is considered implausible; and the Leontief price model (LPM) and the Ghosh price model (GPM) assume that quantity is fixed. This study proposes to consider a supply constraint in the LPM, introducing the price elasticity of demand. This study uses the loss of social surplus (SS) as a damage estimation because production (sales) is less informative as a damage index than profit (margin); that is, production can be any amount if without considering profit, and it does not tell exactly how much profit is lost for each supplier (upstream sector) and buyer (downstream sector). As a model application, this study examines Japan's largest five earthquakes from 1995 to 2017 and the Great East Japan Earthquake (GEJE) in March 2011. The worst earthquake at the peak tends to increase price by 10-20% and decrease SS by 20-30%, when compared with the initial month's prices/production. The worst damage tends to last eight months at most, accumulating 0.5-month-production damage (i.e., the sum of [hypothetical] differences in SS with and without an earthquake [for eight months] is 50% of the initial month production). Meanwhile, the GEJE in the five prefectures had cumulatively, a 25-month-production damage until the temporal recovery at the 37th month.

KEYWORDS: Earthquakes in Japan; input-output analysis; supply constraint

JEL codes: D57, Q54

1. INTRODUCTION

Japan is known as an earthquake-prone country; between 1996 and September 2018, there were 155 earthquakes – an average of 6.7 earthquakes per year – which resulted in human injuries (Japan Meteorological Agency, 2018). Dead or missing people were reported as a result of 20 of these 155 earthquakes, with more than 10 people being reported dead or missing as a result of six of them. Ninety-nine cases resulted not only in human injuries but also in physical damage (houses, school buildings, landslides, window glass, water pipes, and so on). Tsunamis occurred in 18 cases, and more than one-meter tsunamis occurred in three cases (the mortality rate when a person is involved in a one-meter tsunami is almost 100%). Note that in 1995, the Hyogo-ken Nanbu Earthquake (the so-called Great Hanshin Earthquake) resulted in 6,434 deaths and three missing people.

Natural disasters such as earthquakes often disrupt economic activities across supply chains. To effectively use human capital and efficiently transform materials, production supply chains have become more complex (Brown, 2015). The risks of supply chain disruption have also increased because of unplanned and unusual events within complex production supply chains (Mital et al., 2018). Savitz (2012) used the Great East Japan Earthquake (GEJE, Japan) in March 2011 and the major flooding in Thailand in 2011 to highlight the need for manufacturers to apply effective risk-management strategies along supply chains to minimize disruptions. These examples demonstrate the importance of forecasting the economic damage that will result from supply chain disruptions when structuring risk-management schemes for product supply chains.

Economic methods such as computable general equilibrium (CGE) analysis, econometrics, and input-output (IO) analysis (IOA) have been widely used to quantify the economic damage associated with natural disasters, including earthquakes. They have also been used to conduct pre- and post-evaluations of recoveries from economic damage. Among them, IOA can be effective in evaluating economic impacts at the regional/sectoral level through the reduction in intermediate demand. In recent years, studies have used IOA to quantify the environmental loads with respect to greenhouse gas emissions (Kanemoto et al., 2016), water consumption (Feng et al., 2011), land use change (Weinzettel et al., 2013), biodiversity trends (Wilting et al., 2017), and material consumption

(Wiedmann et al., 2015), for example. These loads are included in "environmental footprint (Hoekstra and Wiedmann, 2014)." Although no extant method is versatile enough to evaluate economic damage over the long and short term, IOA is often used to analyze economic damage incurred through the supply chain as a result of large-scale, regional disasters such as floods and hurricanes (Crawford-Brown et al., 2013; Hallegatte, 2008; Li et al., 2013; Okuyama, 2007; Shimoda and Fujikawa, 2012).

This study focuses on an exogenous (flow) damage (i.e., the hypothetical difference of economic scales with and without a disaster in a certain period) to production ("supply constraint") in IOA. The reason for such focus is because we can often know changes in industrial production at the monthly or quarterly levels from specific production statistics (provided by governments, industry organizations, and so on). As an issue, however, IOA cannot basically handle the supply constraint. Four typical IO models are the Leontief quantity model (LQM; Leontief, 1936), the Ghosh quantity model (GQM; Ghosh, 1958), the Leontief price model (LPM), and the Ghosh price model (GPM) (note that these price models were independently developed by Davar (1989) and Oosterhaven (1989)) (Fig. 1). The LQM cannot treat the supply constraint because production is endogenous. In GQM, although value added (or primary input) is exogenous, GQM itself is considered implausible (Oosterhaven, 1988, 1989, 1996, 2012). In LPM and GPM, because the quantity is assumed to be fixed, the supply constraint is not basically applicable.

The purpose of this study is to propose a method that can consider the supply constraint in LPM, introducing the price elasticity of demand. This idea comes from Park (2007), who uniquely interpreted that GPM can consider the supply constraint. This approach requires the common assumptions of IOA, for instance, that the technical coefficient is fixed.

This study modifies Park's (2007) approach in certain aspects. Specifically, this study proposes using the loss of social surplus (SS) as damage instead of the change in production. Production (sales) is less informative as a damage index than profit (margin) because it can be any amount without considering profit. Also, production does not exactly tell how much profit is lost for or how much damage of the supply constraint is passed on to each supplier (upstream sectors) and each buyer (downstream sectors). For example, suppose the supply quantity is constrained to 80%

after the disaster, increasing the price to 125%. Thus, production remains 100%, but the buyers are damaged because they buy smaller quantities at the higher price. Such damage information is available in SS, which is consumer surplus (CS) plus producer surplus (PS).

As a model application, among the 155 earthquakes plus the Hyogo-ken Nanbu Earthquake in 1995, which is included because of the huge impact that earthquake had, this study examines the six largest earthquakes in terms of deaths and missing people (Table I). These earthquakes are: the Hyogo-ken Nanbu Earthquake in January 1995 (hereafter H95Jan), which resulted in 6,434 deaths and three missing people; the Mid Niigata Prefecture Earthquake in October 2004 (N04Oct), with 68 deaths; the Niigata-ken Chuetsu-oki Earthquake in July 2007 (N07Jul), with 15 deaths; the Iwate-Miyagi Nairiku Earthquake in June 2008 (IM08Jun), with 17 deaths and six missing people; the GEJE, with 19,630 deaths and 2,569 missing people; and the 2016 Kumamoto earthquakes in April 2016 (K16Apr), which resulted in 269 deaths.

The structure of this paper is as follows. Section 2 explains the basic IO models. Section 3 models the supply constraint in IOA, following and modifying Park (2007). Section 4 explains the application to earthquakes in Japan. Section 5 shows the estimated results, and Section 6 concludes.

2. BASIC IO MODELS

2.1. Basic Quantity and Price IO Models

Two basic IO models (following Miller and Blair, 2009; and Oosterhaven, 1996) are the Leontief model (LQM and LPM) and the Ghosh model (GQM and GPM) (Fig. 1). Note that to facilitate understanding by comparison, this section follows the explanation in Oosterhaven (1996). LQM ("the demand-driven model") is expressed as:

$$\mathbf{x} = \mathbf{Zi} + \mathbf{Yi} = \mathbf{Zi} + \mathbf{y} = \mathbf{Ax} + \mathbf{y} \tag{1}$$

$\mathbf{x}$ is I-vector total output (or input) per sector: $[x_i]$ where brackets represent a vector or matrix. I means the number of sectors. $\mathbf{Z}$ is I×I-matrix with intermediate outputs (or inputs) per sector: $[z_{ij}]$. $\mathbf{Y}$ is I×M-matrix with final demand (or outputs) per sector: $[y_{im}]$. M means the number of categories in final demand. $\mathbf{i}$ is a summation vector (of one). $\mathbf{A}$ is I×I-matrix with fixed intermediate input coefficients (or technical input coefficients) ($[a_{ij}]$) in a single-region IOA. Note that in a multi-regional IO (MRIO) model, sectors i and j may be in different regions, trading a good from i to j. Thus, the MRIO model terms a_{ij} not as a "technical coefficient" but as "the product of a technical IO coefficient and IO trade coefficient" (Oosterhaven and Hewings, 2014).

$$\mathbf{Z} = \mathbf{A}\hat{\mathbf{x}} \Leftrightarrow \mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1} \tag{2}$$

where the hat (of **x**) means a diagonal matrix. LQM is solved:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{L}\mathbf{y} \tag{3}$$

where **I** is the $I \times I$-identity matrix. **L** is the so-called Leontief inverse (or input inverse), where $\mathbf{L} = [l_{ij}] = (\mathbf{I} - \mathbf{A})^{-1}$.

LPM ("the cost-push price model"; Davar, 1989; Oosterhaven, 1989) is expressed as:

$$\mathbf{p}' = \mathbf{p}'\mathbf{A} + \mathbf{p}'_{\mathrm{v}}\mathbf{C} \tag{4}$$

p is an I-vector of index price $[p_i]$ for sectoral output (unit cost for purchasers). $\mathbf{p}_{\mathrm{v}}$ is an N-vector $[p_{vn}]$ of index price for primary inputs (or value added). **p** and $\mathbf{p}_{\mathrm{v}}$ are usually a unit vector (i.e., one) (however, the lengths I and N are different). **C** is $N \times I$ matrix of fixed primary input coefficients, where **V** is the $N \times I$ matrix of primary inputs (value added, $[v_{ni}]$). N means the number of categories in value added.

$$\mathbf{V} = \mathbf{C}\hat{\mathbf{x}} \Leftrightarrow \mathbf{C} = \mathbf{V}\hat{\mathbf{x}}^{-1} \tag{5}$$

The sum of weights regarding **A** and **C** is equal to one ($\mathbf{i}'\mathbf{A} + \mathbf{i}'\mathbf{C} = \mathbf{i}'$). LPM is solved:

$$\mathbf{p}' = \mathbf{p}'_{\mathrm{v}}\mathbf{C}(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{p}'_{\mathrm{v}}\mathbf{C}\mathbf{L} \tag{6}$$

Meanwhile, GQM ("the supply-driven model") is expressed as:

$$\mathbf{x}' = \mathbf{i}'\mathbf{Z} + \mathbf{i}'\mathbf{V} = \mathbf{i}'\mathbf{Z} + \mathbf{v}' = \mathbf{x}'\mathbf{B} + \mathbf{v}' \tag{7}$$

B is the $I \times I$-matrix, with fixed intermediate output coefficients (or technical output coefficients) ($[b_{ij}]$) in a single-region IOA. Similarly to LQM, an MRIO model terms b_{ij} not as a "technical coefficient" but as "the product of technical IO coefficient and IO trade coefficient" (Oosterhaven and Hewings, 2014).

$$\mathbf{Z} = \hat{\mathbf{x}}\mathbf{B} \Leftrightarrow \mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{Z} \tag{8}$$

The relationship between **A** and **B** is expressed as:

$$\mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{A}\hat{\mathbf{x}} \Leftrightarrow \mathbf{A} = \hat{\mathbf{x}}\mathbf{B}\hat{\mathbf{x}}^{-1} \quad (9)$$

GQM is solved:

$$\mathbf{x}' = \mathbf{v}'(\mathbf{I} - \mathbf{B})^{-1} = \mathbf{v}'\mathbf{G} \quad (10)$$

G is called the Ghosh inverse (or output inverse), where $\mathbf{G} = [g_{ij}] = (\mathbf{I} - \mathbf{B})^{-1}$.

GQM is mathematically equivalent to LPM, given that price is variable and quantity is fixed (Dietzenbacher, 1997). Following Park (2007), recall that $\mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{A}\hat{\mathbf{x}}$, and GQM is solved:

$$\Delta\mathbf{x}' = \Delta\mathbf{v}'(\mathbf{I} - \mathbf{B})^{-1} = \Delta\mathbf{v}'(\mathbf{I} - \hat{\mathbf{x}}^{-1}\mathbf{A}\hat{\mathbf{x}})^{-1} = \Delta\mathbf{v}'(\hat{\mathbf{x}}^{-1}\hat{\mathbf{x}} - \hat{\mathbf{x}}^{-1}\mathbf{A}\hat{\mathbf{x}})^{-1} = \Delta\mathbf{v}'\hat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{x}} \quad (11)$$

Here, suppose that the relative price of primary input changes only in the *l*-th factor (e.g., labor) and does not change in other factors. Let $\Delta\mathbf{v}_l^{p'}$ be the relative change in value added in the *l*-th factor:

$$\Delta\mathbf{v}_l^{p'} = \Delta\mathbf{v}_l'\hat{\mathbf{x}}^{-1} \quad (12)$$

where $\Delta\mathbf{v}_l'$ is the corresponding value added. Substituting $\Delta\mathbf{v}_l^{p'}$ and multiplying $\hat{\mathbf{x}}^{-1}$ in Eq.11:

$$\Delta\mathbf{x}'\hat{\mathbf{x}}^{-1} = \Delta\mathbf{v}_l^{p'}(\mathbf{I} - \mathbf{A})^{-1} = \Delta\mathbf{v}_l^{p'}\mathbf{L} \quad (13)$$

Let $\Delta\mathbf{p}'$ and $\Delta(\mathbf{p}_\mathrm{v}'\mathbf{C})$ be the change ratios in production and primary input, respectively. Note that $\Delta(\mathbf{p}_\mathrm{v}'\mathbf{C})$ does not always mean $\mathbf{C}$ is fixed:

$$\Delta(\mathbf{p}_\mathrm{v}'\mathbf{C}) = (\Delta\mathbf{p}_\mathrm{v}')(\Delta\mathbf{C}) \neq \Delta\mathbf{p}_\mathrm{v}'\mathbf{C} \quad (14)$$

$\Delta\mathbf{p}'$ is expressed:

$$\Delta\mathbf{p}' = \Delta\mathbf{x}'\hat{\mathbf{x}}^{-1} = \Delta\mathbf{v}_l^{p'}\mathbf{L} = \Delta(\mathbf{p}_\mathrm{v}'\mathbf{C})\mathbf{L} \quad (15)$$

Thus, it is exactly the same as LPM, given that quantity is fixed. In other words, GQM can be interpreted as a price model.

Finally, GPM ("the demand-pull price model"; Davar, 1989; Oosterhaven, 1989) is expressed as:

$$\mathbf{p} = \mathbf{B}\mathbf{p} + \mathbf{D}\mathbf{p}_\mathbf{y} \quad (16)$$

D is the $I \times M$-matrix of the fixed final output coefficients:

$$\mathbf{Y} = \hat{\mathbf{x}}\mathbf{D} \Leftrightarrow \mathbf{D} = \hat{\mathbf{x}}^{-1}\mathbf{Y} \quad (17)$$

p is an *I*-vector of index price $[p_i]$ for sectoral input (unit revenue for suppliers), and $\mathbf{p}_\mathrm{y}$ is an *M*-vector $[p_{ym}]$ of index price for final outputs per category. **p** and $\mathbf{p}_\mathrm{y}$ are usually a unit vector (however, the lengths I and M are different). The sum of weights regarding $\mathbf{B}$ and $\mathbf{D}$ is equal to one ($\mathbf{Bi} + \mathbf{Di} = \mathbf{i}$). GPM is solved:

$$\mathbf{p} = (\mathbf{I} - \mathbf{B})^{-1}\mathbf{D}\mathbf{p}_{\mathbf{y}} = \mathbf{G}\mathbf{D}\mathbf{p}_{\mathbf{y}} \tag{18}$$

GPM is mathematically equivalent to LQM, given that the price is fixed and the quantity is variable (Dietzenbacher, 1997). Following Park (2007), recall that $\mathbf{A} = \hat{\mathbf{x}}\mathbf{B}\hat{\mathbf{x}}^{-1}$, and LQM is solved:

$$\Delta\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\Delta\mathbf{y} = (\hat{\mathbf{x}}\hat{\mathbf{x}}^{-1} - \hat{\mathbf{x}}\mathbf{B}\hat{\mathbf{x}}^{-1})^{-1}\Delta\mathbf{y} = \hat{\mathbf{x}}(\mathbf{I} - \mathbf{B})^{-1}\hat{\mathbf{x}}^{-1}\Delta\mathbf{y} \tag{19}$$

By multiplying $\hat{\mathbf{x}}^{-1}$ in Eq.19, the change ratio in production ($\hat{\mathbf{x}}^{-1}\Delta\mathbf{x}$) is expressed as:

$$\hat{\mathbf{x}}^{-1}\Delta\mathbf{x} = \hat{\mathbf{x}}^{-1}\hat{\mathbf{x}}(\mathbf{I} - \mathbf{B})^{-1}\hat{\mathbf{x}}^{-1}\Delta\mathbf{y} = (\mathbf{I} - \mathbf{B})^{-1}\hat{\mathbf{x}}^{-1}\Delta\mathbf{y} = \mathbf{G}\hat{\mathbf{x}}^{-1}\Delta\mathbf{y} \tag{20}$$

Let $\Delta\mathbf{p}$ and $\Delta(\mathbf{D}\mathbf{p}_{\mathbf{y}})$ be the change ratios in total production and final demand, respectively. Note that $\Delta(\mathbf{D}\mathbf{p}_{\mathbf{y}})$ does not always mean $\mathbf{D}$ is fixed:

$$\Delta(\mathbf{D}\mathbf{p}_{\mathbf{y}}) = (\Delta\mathbf{D})(\Delta\mathbf{p}_{\mathbf{y}}) \neq \mathbf{D}\Delta\mathbf{p}_{\mathbf{y}} \tag{21}$$

$\Delta\mathbf{p}$ is expressed as:

$$\Delta\mathbf{p} = \hat{\mathbf{x}}^{-1}\Delta\mathbf{x} = \mathbf{G}\hat{\mathbf{x}}^{-1}\Delta\mathbf{y} = \mathbf{G}\Delta(\mathbf{D}\mathbf{p}_{\mathbf{y}}) \tag{22}$$

Thus, it is exactly the same as GPM, given that the price is fixed, In other words, GPM can be interpreted as a quantity model.

2.2. Two Implicit Assumptions

Park (2007) argues that IOA has two implicit assumptions: the newly required value added and final demand (Ghosh, 1958). Regarding the former, the ratio of the newly required value added over total input is defined as **c**:

$$\mathbf{c} = \mathbf{i}'\mathbf{C} = \mathbf{i}'\mathbf{V}\hat{\mathbf{x}}^{-1} = \mathbf{v}'\hat{\mathbf{x}}^{-1} \tag{23}$$

c is an *I*-vector and indeed the absolute price of primary inputs:

$$\mathbf{c} = \mathbf{p}_{\mathrm{v}}'\mathbf{C} = \mathbf{i}'\mathbf{V}\hat{\mathbf{x}}^{-1} = \mathbf{v}'\hat{\mathbf{x}}^{-1} \Leftrightarrow \Delta\mathbf{c} = \Delta(\mathbf{p}_{\mathrm{v}}'\mathbf{C}) = \Delta(\mathbf{i}'\mathbf{V}\hat{\mathbf{x}}^{-1}) = \Delta(\mathbf{v}'\hat{\mathbf{x}}^{-1}) \tag{24}$$

$\Delta(\mathbf{v}'\hat{\mathbf{x}}^{-1})$ means either or both **x** and **v** change. The newly required value added is expressed as:

$$\Delta\mathbf{v}' = \Delta\mathbf{v}'\hat{\mathbf{x}}^{-1}\hat{\mathbf{x}} = (\Delta\mathbf{c})\hat{\mathbf{x}} \tag{25}$$

Here, we assume that $(\Delta\mathbf{c})\hat{\mathbf{x}}$ is equal to $\mathbf{c}\widehat{\Delta\mathbf{x}}$, meaning that a certain change in **c** is passed only onto the change in production:

$$(\Delta\mathbf{c})\hat{\mathbf{x}} = \mathbf{c}\widehat{\Delta\mathbf{x}} = \Delta\mathbf{x}'\hat{\mathbf{c}} \tag{26}$$

Eq.26 can be solved because of multiplying $\mathbf{x}'$ and $\mathbf{c}$ (both *I*-vectors) in an element wise way. By multiplying $\hat{\mathbf{x}}^{-1}$ in Eq.26:

$$\Delta(\mathbf{p}_{\mathrm{v}}'\mathbf{C}) = \Delta\mathbf{c} = (\Delta\mathbf{c})\hat{\mathbf{x}}\hat{\mathbf{x}}^{-1} = \mathbf{c}\widehat{\Delta\mathbf{x}}\hat{\mathbf{x}}^{-1} = \Delta\mathbf{x}'\hat{\mathbf{x}}^{-1}\hat{\mathbf{c}} = \Delta\mathbf{p}'\hat{\mathbf{c}} \tag{27}$$

Notice that $\Delta\mathbf{x}'\hat{\mathbf{x}}^{-1}$ is $\Delta\mathbf{p}'$, given that quantity is fixed (because of LPM). Thus, this implies that a certain change in the primary input price ($\Delta(\mathbf{p}'_{\mathbf{v}}\mathbf{C})$) should be transferred from the change in the total input price ($\Delta\mathbf{p}'$) via $\hat{\mathbf{c}}$.

Similarly, regarding the latter, the ratio of the final demand ($\mathbf{y}$) over total output ($\mathbf{x}$) is defined as **d**:

$$\mathbf{d} = \mathbf{D}\mathbf{i} = \hat{\mathbf{x}}^{-1}\mathbf{Y}\mathbf{i} = \hat{\mathbf{x}}^{-1}\mathbf{y} \tag{28}$$

d is an *I*-vector, and indeed the change ratio of final demand, given that price is fixed (because of GPM):

$$\mathbf{d} = \mathbf{D}\mathbf{p}_{\mathbf{y}} = \hat{\mathbf{x}}^{-1}\mathbf{y} \Leftrightarrow \Delta\mathbf{d} = \Delta\left(\mathbf{D}\mathbf{p}_{\mathbf{y}}\right) = \Delta(\hat{\mathbf{x}}^{-1}\mathbf{y}) \tag{29}$$

$\Delta(\hat{\mathbf{x}}^{-1}\mathbf{y})$ means either or both of **x** and **y** change. The newly required final demand is expressed as:

$$\Delta\mathbf{y} = \hat{\mathbf{x}}\hat{\mathbf{x}}^{-1}\Delta\mathbf{y} = \hat{\mathbf{x}}(\Delta\mathbf{d}) \tag{30}$$

Here, we assume that $\hat{\mathbf{x}}(\Delta\mathbf{d})$ is equal to $\widehat{\Delta\mathbf{x}}\mathbf{d}$, meaning a certain change in **d** is passed only onto the change in production:

$$\hat{\mathbf{x}}(\Delta\mathbf{d}) = \widehat{\Delta\mathbf{x}}\mathbf{d} = \hat{\mathbf{d}}\Delta\mathbf{x} \tag{31}$$

Eq.31 can be solved because of multiplying $\mathbf{x}$ and $\mathbf{d}$ (both *I*-vectors) in an element wise way. By multiplying $\hat{\mathbf{x}}^{-1}$ in Eq.31:

$$\Delta\left(\mathbf{D}\mathbf{p}_{\mathbf{y}}\right) = \Delta\mathbf{d} = \hat{\mathbf{x}}^{-1}\hat{\mathbf{x}}(\Delta\mathbf{d}) = \hat{\mathbf{x}}^{-1}\widehat{\Delta\mathbf{x}}\mathbf{d} = \hat{\mathbf{d}}\hat{\mathbf{x}}^{-1}\Delta\mathbf{x} = \hat{\mathbf{d}}\Delta\mathbf{p} \tag{32}$$

Notice that $\hat{\mathbf{x}}^{-1}\Delta\mathbf{x}$ is $\Delta\mathbf{p}$, given that price is fixed (because of GPM). This implies that a certain change ratio of final demand ($\Delta\left(\mathbf{D}\mathbf{p}_{\mathbf{y}}\right)$) should be transferred from the change ratio of production ($\Delta\mathbf{p}$) via $\hat{\mathbf{d}}$.

2.3. Implausibility of the IO Models

In the IO literature, Oosterhaven (1988) has argued that GQM is implausible (see Supplementary Information A). In summary, GQM converts (delivers) the additional primary input ($\Delta\mathbf{v}$) into final demand ($\mathbf{y}$) in a perfectly elastic way (without any technological relationship), meaning that "consumers will buy whatever is supplied to them" (Oosterhaven, 2012, p.106). Implausibility implies that intermediate demand (input ratios) varies arbitrarily and that a production function is not necessary. Adding to the debate on implausibility (Gruver, 1989; Rose and Allison, 1989), Dietzenbacher (1997) argued that the four IO models (LQM, GQM, LPM, and GPM) should be divided into either the demand-pull (LQM and GPM, given the fixed price) or cost-push models (LPM and GQM, given the fixed quantity) (Section 2.1; Fig. 1).

3. MODELING OF SUPPLY CONSTRAINT

3.1. Introduction of This Section

This section proposes the supply-driven IO model with reference to Park (2007; the unpublished paper). As in Section 2, a basic IOA can analyze only the following four changes: final demand ($\Delta\mathbf{y}$) in LQM (Eq.3) and price for final outputs ($\Delta\mathbf{p_y}$) in GPM (Eq.18) as the demand-pull models; and value added ($\Delta\mathbf{v}'$) in GQM (Eq.10) and price for value added ($\Delta\mathbf{p}'_\mathbf{v}$) in LPM (Eq.6) as the cost-push models.

As an issue, the supply constraint is usually a quantity issue on the supply side, but GQM itself is considered implausible (Sections 2.3 and 3.2). Instead of GQM, Park (2007) proposes to use GPM (Eqs.22–32) for the supply constraint by introducing the price elasticity of demand (Section 3.3). Note that Park (2009; the unpublished paper) applied this approach to conduct an economic analysis of the U.S. oil industry based on changes in crude oil prices (see Supplementary Information B).

This study modifies Park (2007) in the following two ways. First, because GPM is a demand-side model, this study supposes that LPM is appropriate for analyzing the supply constraints (Section 3.5). Second, because production itself is less informative as a damage index than profit, this study proposes to use the loss of SS as the damage index (Sections 3.4 and 3.6; for comparison between

IOA, this study, and CGE, see Supplementary Information C). Section 3.7 (Supplementary Information D) discusses how this study relates to the methods proposed in the previous studies regarding the seven issues.

3.2. The Difficulty of Supply Constraint in IOA

An exogenous shock such as a disaster often disrupts supply (i.e., supply constraint). Although we often know how much production decreases due to a shock via sectoral production statistics (typically at the monthly level), the supply constraint is difficult to consider in IOA. First, the supply constraint is usually a quantity issue. Even if price rises, quantity decreases; however, the fact that consumers will reduce the purchase quantity because of the price is just a reflection of a supply-demand balance. Therefore, IO price models are usually inadequate because they assume quantity is fixed (however, Dietzenbacher (1997) interpreted GPM as a quantity model; Section 2.1).

LQM cannot usually handle the supply constraint because LQM assumes that total output is endogenous. In the literature, the inoperability IO model (e.g., Haimes and Jiang, 2001; Santos, 2006) considers the supply constraint; however, this model is regarded as suspicious for usability because it is based on LQM (Oosterhaven, 2017).

Note that many disaster studies have used LQM (e.g., Crawford-Brown et al., 2013; Hallegatte, 2008; Li et al., 2013; Okuyama, 2007; Steenge and Bočkarjova, 2007). A basic application is to adopt the survival coefficient (or production capacity) $\boldsymbol{\Theta} = [\theta_i]$ for total output (or input) ($\Delta\mathbf{x}$) in sector i. θ_i is unity before a disaster and $0 \le \theta_i \le 1$ after a disaster.

$$\widehat{\boldsymbol{\Theta}}\mathbf{x} = \mathbf{x} + \Delta\mathbf{x} \tag{33}$$

Again, however, the surviving total output ($\widehat{\boldsymbol{\Theta}}\mathbf{x}$) is basically endogenous.

Finally, GQM is applied in some disaster studies (e.g., for a recent survey, see Galbusera and Giannopoulos, 2018; Shimoda and Fujikawa, 2012). GQM is numerically capable if we know an exogenous change in primary input ($\Delta\mathbf{v}$) due to a supply constraint in Eq.10. However, GQM is not popular because of its implausibility (Oosterhaven, 1988, 2017).

3.3. Supply Constraint in Park (2007)

Park (2007) has uniquely considered the supply constraint in GPM. Note that Park (2009) adopts a similar method (see Supplementary Information B). Park (2007) first proposes that the supply constraint may decrease the quantity and increase the price as in basic economics. In Fig. 2, S and D are basic supply and demand curves; E is an equilibrium; and subscripts 0 and 1 are before and after the constraint, respectively. Suppose the demand curve is fixed; if the quantity is constrained from Q_0 to Q_1, the supply curve moves from S_0 to S_1, depending on the fixed demand curve. Thus, the market price increases from P_0 to P_1, and production will change from Q_0 times P_0 to Q_1 times P_1.

Park (2007) proposes using GPM for the supply constraint in the following four steps (A1 to A4; Fig. 3). A1) Output quantity is exogenously constrained in certain sectors. A2) Using A1 and the exogenous price elasticity of demand (ε), the price of final outputs (Δp_y) changes (increases). A3) The spillover effect of Δp_y changes (increases) the input price ($\Delta\tilde{\mathbf{p}}$) (where tilde means the estimation or spillover effect in this study). A4) Based on A3, input quantity is estimated.

Specifically, (A1) the price elasticity of demand (ε) in sector i is exogenously defined as:

$$\varepsilon_i = \frac{\Delta q_i / q_i}{\Delta p_i / p_i} \tag{34}$$

ε is the arc elasticity here (not the point elasticity). Let the base price (p_i) be one and the base quantity (q_i) be equal to x_i ($=p_i q_i$). The change of price is expressed as:

$$\Delta p_i = \frac{\Delta q_i / q_i}{\varepsilon_i / p_i} = \frac{\Delta q_i}{q_i \varepsilon_i} \tag{35}$$

We may use the survival coefficient θ_i instead of the quantity ratio:

$$\frac{q_i + \Delta q_i}{q_i} = \theta_i \Leftrightarrow \frac{\Delta q_i}{q_i} = \theta_i - 1 \tag{36}$$

A2) The newly required price of final output (($\Delta(\mathbf{Dp_y})$) is calculated (Eq.32) as follows:

$$\Delta(\mathbf{Dp_y}) = \hat{\mathbf{d}}\Delta\mathbf{p} = \hat{\mathbf{d}}\left[\frac{\Delta q_i}{q_i \varepsilon_i}\right] = \hat{\mathbf{d}}\left[\frac{\theta_i - 1}{\varepsilon_i}\right] \tag{37}$$

A3) The spillover change in price ($\Delta\tilde{\mathbf{p}}$) is calculated (Eq.22):

$$\Delta\tilde{\mathbf{p}} = \mathbf{G}\Delta(\mathbf{Dp_y}) = \mathbf{G}\hat{\mathbf{d}}\left[\frac{\Delta q_i}{q_i \varepsilon_i}\right] = \mathbf{G}\hat{\mathbf{d}}\left[\frac{\theta_i - 1}{\varepsilon_i}\right] \tag{38}$$

A4) Based on A3 and ε, the spillover change in input quantity ($\Delta\tilde{q}_i$) is estimated. Because Park (2007) does not specify this procedure, Subsection 3.4 discusses it.

3.4. Generalization of Elasticity Between Price and Quantity

A feature of Park (2007) is the introduction of the price elasticity of demand into IOA. As Oosterhaven (1996) pointed out, IOA usually assumes that price (p) and quantity (q) of production (x) are independent of each other. This study presupposes that changes in production are not adequate to use as a damage index because, unlike profit, production does not tell exactly how much damage to the supply constraint is passed along to each supplier (upstream sectors) and each buyer (downstream sectors). For example, suppose the supply quantity is constrained to 80%, increasing the price to 125%. Thus, production is 100%, and the suppliers may not be damaged; however, the buyers will be negatively affected because they will buy smaller quantities at the higher price.

In IOA, even if price changes exogenously by Δp_i in sector i, because quantity does not change ($\Delta q_i = 0$), production increases by $\Delta p_i x_i$:

$$(p_i + \Delta p_i)(q_i + \Delta q_i) = (1 + \Delta p_i)x_i = x_i + \Delta p_i x_i \tag{39}$$

where $(p_i = 1)$ and $(q_i = x_i)$.

In Park (2007), quantity is elastic with respect to price:

$$\varepsilon_i = \frac{\Delta q_i / q_i}{\Delta p_i / p_i} = \frac{\Delta q_i}{\Delta p_i x_i} \Longrightarrow \Delta q_i = \varepsilon_i \Delta p_i x_i \tag{40}$$

If price changes exogenously by Δp_i, production will increase by $(1 + \varepsilon_i + \varepsilon_i \Delta p_i)\Delta p_i x_i$:

$$(p_i + \Delta p_i)(q_i + \Delta q_i) = (1 + \Delta p_i)(x_i + \varepsilon_i \Delta p_i x_i) = x_i + (1 + \varepsilon_i + \varepsilon_i \Delta p_i)\Delta p_i x_i \tag{41}$$

Notice that Eq.39 is a special form of Eq.41, assuming $(1 + \varepsilon_i + \varepsilon_i \Delta p_i)$ is one.

$$(1 + \varepsilon_i + \varepsilon_i \Delta p_i) = 1 \Longrightarrow \varepsilon_i(1 + \Delta p_i) = 0 \tag{42}$$

Thus, IOA usually assumes ε_i is 0. Δp_i is not usually –1 because if so, a price $(p_i + \Delta p_i)$ becomes zero.

Note that the supply constraint usually increases price $(\Delta p_i > 0)$. Therefore, production (Eq.41) will decrease when $(1 + \varepsilon_i + \varepsilon_i \Delta p_i)$ is negative:

$$1 + \varepsilon_i + \varepsilon_i \Delta p_i = 1 + \varepsilon_i(1 + \Delta p_i) < 0 \Leftrightarrow \varepsilon_i < -\frac{1}{1 + \Delta p_i} \tag{43}$$

Eq.43 holds when ε_i is elastic to some degree (at least less than –1 when $\Delta p_i = 0$). Otherwise, production will even increase after the supply constraint.

3.5. Extension to the Cost-Push Price Model

This and the next subsections aim to address two issues in Park (2007). This study argues that GPM in Park (2007) is inadequate for making economic interpretations (of the supply constraint), which is consistent with the assumptions in the following two points (see Subsection 2.3). First, GPM is a demand-pull model (Dietzenbacher, 1997), and hence, it is a demand-side analysis (i.e., the demand constraint). Second, if we are following Dietzenbacher (1997), GPM is a "quantity" model (Eqs.19–22), and therefore, GPM cannot handle price change. Thus, this study supposes that LPM is adequate for the supply constraint. First, LPM is the cost-push model and is for the supply-side analysis. Second, LPM can handle price change.

Specifically, this study proposes to use LPM in the following four steps (B1–B4; Fig. 3). B1) Input quantity is exogenously constrained in certain sectors. B2) Using B1 and the exogenous price elasticity of demand, the price of primary inputs ($\Delta\mathbf{p}_\mathrm{v}$) changes (increases) from Eq.27:

$$\Delta(\mathbf{p}_\mathrm{v}'\mathbf{C}) = \Delta\mathbf{p}'\hat{\mathbf{c}} = \left[\frac{\Delta q_i}{q_i \varepsilon_i}\right]' \hat{\mathbf{c}} = \left[\frac{\theta_i - 1}{\varepsilon_i}\right]' \hat{\mathbf{c}} \tag{44}$$

B3) The spillover effect of $\Delta\mathbf{p}_\mathrm{v}$ changes (increases) output price ($\Delta\tilde{\mathbf{p}}$) (Eq.15).

$$\Delta\tilde{\mathbf{p}}' = \Delta(\mathbf{p}_\mathrm{v}'\mathbf{C})\mathbf{L} = \Delta\mathbf{p}'\hat{\mathbf{c}}\mathbf{L} = \left[\frac{\Delta q_i}{q_i \varepsilon_i}\right]' \hat{\mathbf{c}}\mathbf{L} = \left[\frac{\theta_i - 1}{\varepsilon_i}\right]' \hat{\mathbf{c}}\mathbf{L} \tag{45}$$

B4) based on B3 and ε, spillover change in output quantity ($\Delta\tilde{q}$) is estimated, such as from Eq.40:

$$\Delta\tilde{q}_i = \varepsilon_i \Delta\tilde{p}_i x_i \tag{46}$$

Note that the elasticities (ε) are set as the same for Eqs.44 and 46 for simplification, but they can be different: such as ε^s (for supply "s") in Eq.44 and ε^d (for demand "d") in Eq.46.

3.6. Social Surplus Loss as a Damage of Supply Constraint

The other issue is that Park (2007) estimates production as damage, which is obtained by multiplying total inputs and price changes in the next period (x times Δp; see Supplementary Information B). Unlike profit, however, changes in production do not exactly tell us how much damage is passed on to each supplier (upstream sectors) and each buyer (downstream sectors). Even if production increases after the supply constraint (as in Eqs.39–43), consumers, in particular, may be damaged because the constraint decreases quantity and increases price.

Instead, this study proposes to use the loss of SS as the damage because it can identify the damage incurred by each buyer and seller. Note that the estimation of SS is common practice in CGE applications (e.g., Koks et al. (2016) that conduct both IOA and CGE for flood analysis). CGE looks ideal for disaster analysis because it is theoretically consistent; however, CGE is usually much harder to estimate than IOA (see Supplementary Information C).

For simplicity, as in Fig. 2, this study supposes that the demand (D) and supply (S) curves are linear, and that D does not change, whereas S changes from S_0 to S_1 (note that S_0 and S_1 are supposed to go through the origin O). Specifically, the demand curve (D) in sector i has a slope of $\frac{1}{\varepsilon_i x_i}$ from Eqs.34–35 and hence, has an intercept $\left(1-\frac{1}{\varepsilon_i}\right)$.

Suppose that before the disaster, quantity is production ($q_i = x_i$) and price is one ($p_i = 1$) in sector i. SS (ss_i^{before}) before the supply constraint (in sector i) is $\Delta \mathrm{AOE_0}$, where CS (cs_i^{before}) is $\Delta \mathrm{AP_0E_0}$, and PS (ps_i^{before}) is $\Delta \mathrm{OP_0E_0}$ (notice that PS is half of x_i).

$$ss_i^{before} = cs_i^{before} + ps_i^{before} = \Delta \mathrm{AOE_0} = \frac{1}{2}\cdot \mathrm{AO}\cdot \mathrm{P_0E_0} = \frac{1}{2}\cdot\left(1-\frac{1}{\varepsilon_i}\right)\cdot x_i = \left(\frac{1-\varepsilon_i}{2}\right)x_i = -\frac{x_i}{2\varepsilon_i}+\frac{x_i}{2} \tag{47}$$

$$cs_i^{before} = \Delta \mathrm{AP_0E_0} = \frac{1}{2}\cdot \mathrm{AP_0}\cdot \mathrm{P_0E_0} = \frac{1}{2}\cdot\left(-\frac{1}{\varepsilon_i}\right)\cdot x_i = -\frac{x_i}{2\varepsilon_i} \tag{48}$$

$$ps_i^{before} = \Delta \mathrm{OP_0E_0} = \frac{1}{2}\cdot \mathrm{OP_0}\cdot \mathrm{P_0E_0} = \frac{1}{2}\cdot 1\cdot x_i = \frac{x_i}{2} \tag{49}$$

Meanwhile, suppose that after the disaster in sector i, the price changes from one to

$(1+\Delta\tilde{p}_i)$ from Eq.45, whereas quantity changes from x_i to $(1+\varepsilon_i\Delta\tilde{p}_i)x_i$ from Eq.46. Thus, new production (x_i^{after}) is calculated:

$$x_i^{after} = (1+\Delta\tilde{p}_i)\cdot(1+\varepsilon_i\Delta\tilde{p}_i)x_i \tag{50}$$

SS after the supply constraint (ss_i^{after}) is ΔAOE_1, where CS (cs_i^{after}) is ΔAP_1E_1, and PS (ps_i^{after}) is ΔOP_1E_1.

$$\begin{aligned} ss_i^{after} &= cs_i^{after} + ps_i^{after} = \Delta \mathrm{AOE}_1 = \frac{1}{2}\cdot \mathrm{AO}\cdot \mathrm{P_1E_1} = \frac{1}{2}\cdot\left(1-\frac{1}{\varepsilon_i}\right)\cdot(1+\varepsilon_i\Delta\tilde{p}_i)x_i \\ &= (1+\varepsilon_i\Delta\tilde{p}_i)\cdot ss_i^{before} \end{aligned} \tag{51}$$

$$\begin{aligned} cs_i^{after} &= \Delta \mathrm{AP_1E_1} = \frac{1}{2}\cdot \mathrm{AP_1}\cdot \mathrm{P_1E_1} = \frac{1}{2}\cdot\left[\left(1-\frac{1}{\varepsilon_i}\right)-(1+\Delta\tilde{p}_i)\right]\cdot(1+\varepsilon_i\Delta\tilde{p}_i)x_i \\ &= \frac{1}{2}\cdot\left(1-\frac{1}{\varepsilon_i}\right)\cdot(1+\varepsilon_i\Delta\tilde{p}_i)x_i - \frac{1}{2}\cdot(1+\Delta\tilde{p}_i)\cdot(1+\varepsilon_i\Delta\tilde{p}_i)x_i \\ &= ss_i^{after} - \frac{x_i^{after}}{2} \end{aligned} \tag{52}$$

$$ps_i^{after} = \Delta \mathrm{OP_1E_1} = \frac{1}{2}\cdot \mathrm{OP_1}\cdot \mathrm{P_1E_1} = \frac{1}{2}\cdot(1+\Delta\tilde{p}_i)\cdot(1+\varepsilon_i\Delta\tilde{p}_i)x_i = \frac{x_i^{after}}{2} \tag{53}$$

Therefore, SS (ΔAOE_0 and ΔAOE_1) are two triangles, and they have the same base (AO) and different height, P_0E_0 (=Q_0) and P_1E_1 (=Q_1), depending only on the change in height (quantity).

Specifically, this study proposes changes in SS, CS, and PS as damage indicators for the whole industry, the downstream sectors, and the upstream sectors, respectively. In sector i, the loss of SS (Δss_i) is ss_i^{before} minus ss_i^{after}:

$$\Delta ss_i = ss_i^{before} - ss_i^{after} = ss_i^{before} - (1+\varepsilon_i\Delta\tilde{p}_i)\cdot ss_i^{before} = -\varepsilon_i\Delta\tilde{p}_i\cdot ss_i^{before} \tag{54}$$

The loss of CS (Δcs_i) is cs_i^{before} minus cs_i^{after}, which is a trapezoid $P_1P_0E_0E_1$:

$$\begin{aligned} \Delta cs_i &= cs_i^{before} - cs_i^{after} = \frac{1}{2}\cdot(\mathrm{P_1E_1}+\mathrm{P_0E_0})\cdot \mathrm{P_1P_0} = \frac{1}{2}\cdot\big((1+\varepsilon_i\Delta\tilde{p}_i)x_i + x_i\big)\cdot\Delta\tilde{p}_i \\ &= \frac{\Delta\tilde{p}_i(2+\varepsilon_i\Delta\tilde{p}_i)}{2}\cdot x_i \end{aligned} \tag{55}$$

The loss of PS (Δps_i) is ps_i^{before} minus ps_i^{after}:

$$\Delta ps_i = ps_i^{before} - ps_i^{after} = \frac{x_i^{after}}{2} - \frac{x_i}{2} = -\frac{\Delta\tilde{p}_i(1+\varepsilon_i+\varepsilon_i\Delta\tilde{p}_i)}{2}\cdot x_i \tag{56}$$

3.7. Applications to the Approaches in the Previous Studies

Some readers may wonder how this study relates to the methods proposed in the previous studies. Due to space limitations, Supplementary Information D briefly discusses the following seven items: the endogenous recovery for the survival coefficient (D.2), the sequential interindustry models in Romanoff (1984) and Okuyama et al. (2004) (D.3), the impact on transportation networks in Sohn et al. (2004) and Kim et al. (2002) (D.4), the input-occupancy-output model in Chen (1990) and Chen et al. (2005) (D.5), the extension to the CGE model in Kratena et al. (2013; 2017) and Kratena and Streicher (2017) (D.6), spatial substitution and price multipliers (D.7), and the supply constraint in GQM (D.8).

4. APPLICATION TO EARTHQUAKES IN JAPAN

4.1. Multi-Regional IO Table in Japan

As a model application, this study examines the effect of supply constraint in the largest earthquakes in Japan (Table I). This study uses the 2005 MRIO table at the prefecture level (Hasegawa et al., 2015), which covers the 47 prefectures of Japan. This table includes 80 industry sector classifications (#1 to #80), where 54 sectors from #2 to #55 are mining and manufacturing sectors (industrial sectors), and 26 sectors (#1, #56 to #80) are agricultural and service sectors (non-industrial sectors) (see Supplementary Information Tables S4–S9). Thus, there are 3,760 industry-prefectures (80 sectors in 47 prefectures). Because of the data restriction for production capacity, this study examines the 54 mining and industrial sectors out of 80 sectors.

An important feature of earthquakes is that the resultant damage does not tend to spill over to other prefectures. An earthquake with a large magnitude (e.g., M8.0 or more) will shake greatly in the prefecture closest to the epicenter (e.g., "Shindo" [seismic intensity scale in Japan] is "lower-five" or above), increasing the risk of human injuries and buildings collapsing. Meanwhile, it will not shake as much in other prefectures far from the epicenter (e.g., Shindo is four or below).

As an exception, however, the GEJE damaged a vast area across prefectures (Hayes et al., 2017). The GEJE not only caused damage as a result of the earthquake, but also due to the tsunami (washing away coastal housing, other buildings, and infrastructure; power problems associated with the Fukushima nuclear power plant accident; and medical problems). This explains why the GEJE is referred to as a triple disaster (Managi and Guan, 2017). The triple disaster also affected undamaged prefectures indirectly in terms of power outages, disruption to logistics and supply chains, and so on. Thus, the prefectural MRIO table is suitable for analyzing huge disasters such as the GEJE because it can consider damage incurred across different prefectures.

The reason for using the 2005 version of the MRIO table (Hasegawa et al., 2015) is that the growth rate of nominal gross domestic product (GDP) is meager between 1995 and 2016 (approximately 0.21% on average): 516 trillion (T), 525T, and 539T Japanese yen (JPY) in 1995, 2005, and 2016, respectively (Cabinet Office, Government of Japan, 2018) (i.e., the so-called lost two decades). Because the industrial structure may change non-trivially over time, however, it is assumed herein that the industrial structure remained as per 2005 during all periods.

The original MRIO table contains annual values, but this study uses monthly values, simply dividing the annual value by 12 (months). If necessary, the production value can be seasonally adjusted. As in GDP statistics, a popular method is to create "centered ratios" for every month by using the (past) 12-month centered moving average. Note that if the input coefficient varies every month, it will require the IO table of each month.

Production ($\mathbf{x}$) at the monthly level is 80,793 billion (B) JPY (100%) for all sectors, 25,263B JPY (31%) for the 54 mining and industrial sectors, and 55,530B JPY (69%) for the other 26 sectors. Similarly, final demand ($\mathbf{y}$) at the monthly level is 46,870B JPY (100%) for all sectors, 11,455B JPY (24%) for the 54 mining and industrial sectors, and 35,415B JPY (76%) for the others.

4.2. Research Settings

As research settings (Table I), the focal prefectures are Hyogo for H95Jan, Niigata for N04Oct and N07Jul, Iwate and Miyagi for IM08Jun, and Kumamoto for K16Apr. Those for GEJE are

Fukushima, Iwate, Miyagi, Ibaraki, and Chiba (FIMIC prefectures), which experienced the triple disaster, and non-FIMIC prefectures (i.e., 42 of the 47 prefectures), which experienced power outages and disruption to logistics and supply chains. As the selection criteria, the prefecture that was closest to the epicenter is focused. However, in the case of IM08Jun, because the epicenter is near the prefectural border between Iwate and Miyagi, we have chosen two prefectures exceptionally.

Regarding the initial and occurrence terms, the initial month before each earthquake (t=0) is set to May 1995 for H95Jan, September 2004 for N04Oct, June 2007 for N07Jul, May 2008 for IM08Jun, March 2016 for K16Apr, and February 2011 for GEJE. Similarly, the month in which each earthquake occurred (t=1) is set to the next months, except for January 1995 in H95Jan. Regarding H95Jan, the month before the disaster (t=0) is set as May 1995 because data were unavailable for December 2014, and production capacity in 1995 was at its highest in May. The analysis periods are 12 months for H95Jan, N04Oct, N07Jul, IM08Jun, and K16Apr, and 48 months for GEJE.

4.3. Data: Production Capacity

Regarding production capacity (θ), this study uses seasonally adjusted indices of industrial production (IIP) published by the statistics office of each prefecture (at different points in time) such as the Hyogo prefecture (2017) for H95Jan, and the Statistics division of the Niigata prefecture (2018) for N04Oct and N07Jul. Note that the Ministry of Economy, Trade, and Industry, Japan (2018) summarizes each prefectural IIP since January 2008.

IIP covers production (in all prefectures), shipments, and inventories, and this study uses IIP because it has abundant production data as an actual index. Because of the real index, however, IIP has a drawback in that it is affected not only by the direct effect of disaster, but also by the indirect effect among sectors, which may be somewhat mitigated by the inventories (see Supplementary Information E).

Because IIP only covers the mining and industrial sectors, analysis is restricted herein to the 54 mining and industrial sectors (#2 to #55) out of 80 sectors in the MRIO table (see Supplementary Information Tables S4–S9). As an issue, however, the IIP sector classification differs from the MRIO table classification (80 sectors). This study uses the common 26-sector classification, connecting the industrial classification of the MRIO table (from #1 to #80) and the IIP id (from #1 to #26). Because there are missing values (i.e., missing sectors) in certain prefectures, this study substitutes another similar IIP id for missing values (see Supplementary Information Tables S4–S5).

The production capacity at t for sector i ($\theta_i(t)$) is configured:

$$\theta_i(t) = \begin{cases} IIP_i(t)/IIP_i(0) & if\ i \in K \\ 1 & if\ i \notin K \end{cases} \tag{57}$$

where $IIP_i(t)$ denotes the original IIP in sector i at month t. K means the set of damaged areas/sectors, and $\theta_i(t)$ is 1 when $i \notin K$. Supplementary Information for the raw dataset includes $\theta_i(t)$ $(i \in K)$ at IIP id, with missing values for each disaster (Excel sheets: H95Jan, N04Oct, N07Jul, IM08Jun, K16Apr, and GEJE) and information on IO id (“ioid”), IIP id (“iipid”), and area id (48 prefectures in “areaid”).

4.4. Data: Price Elasticity of Demand

To estimate price elasticity (ε), this study uses the following regression model in log form:

$$\ln q_{it} = \sum_i D_i \ln\alpha_i + \sum_i D_i \varepsilon_i \ln p_{it} + e_{it} \tag{58}$$

where q is quantity and p is price in sector i in year t. D_i is a dummy variable (0 or 1) for sector i. ε is the coefficient of the log price, representing the price elasticity of demand. $\ln\alpha_i$ is a constant term in each sector i, and e is an error term. Note that this study uses industrial dummy variables to estimate the constant term ($\ln\alpha_i$) and price elasticity (ε_i; by using interaction terms).

Regarding the data, this study uses the Japan Industrial Productivity (JIP) Database 2018 provided by the Research Institute of Economy, Trade, and Industry, Japan (2019). The database includes gross output data at real value (in chain-linked sectoral 2011 prices) and nominal value in 100 unique JIP sectors for 22 years (1994 to 2015), and there are 2,194 observations because nursing care (#95) has six missing values. Thus, we can calculate the sectoral deflator (price) by dividing the nominal value by the real value (where the deflator is one in 2011). Using the real gross output as quantity (q) and the sectoral deflator as price (p), this study estimated the price elasticity of demand (ε) in each of 100 JIP sectors (see Supplementary Information Tables S10–S11).

Note that the 100 JIP sectors are different from the 80 sectors in the MRIO table again. Thus, this study made the weighted average ε for 17 summarized sectors to connect with the 80 MRIO sectors (by using the real gross output as of 2005), so that all values become negative. In Table II, the price elasticity (ε) is –1.305 in total sectors (#1–17), –0.717 in the manufacturing and mining sectors (#1–6; the focus of this study), and –1.598 in the agriculture and service sectors (#7–17).

4.5. Previous Studies Concerning Indirect Damage Estimation: H95Jan and GEJE

In disaster studies, the loss of SS is not widespread for estimating damage. Instead, two popular damages are direct damage (e.g., damage to capital stock) and indirect damage (e.g., flow damage due to the spillover effect). This study supposes that the loss of SS is similar to indirect damage because it does not consider the damage to capital stock and so on. In other words, indirect damage referred to in the previous studies consists of damage to buyers (downstream sectors) and sellers (upstream sectors), which are similar to the losses of CS and PS, respectively. This study supposes that the reason SS is not popular is that CS is difficult to estimate (although PS is easy). CS is calculated from the difference between the reservation price (i.e., willingness-to-pay price) and transaction price. However, the reservation price is usually difficult to estimate.

Two previous studies that estimated damage due to H95Jan (Toyoda and Kouchi, 1997) and GEJE (Hayashi, 2012) are introduced for comparative purposes (see Supplementary Information F). Toyoda and Kouchi (1997) estimated that the indirect damage caused by H95Jan for one year was 1,203B JPY for the industrial sectors (in ten cities and ten towns in Hyogo). Meanwhile, regarding Hayashi (2012), the indirect damage caused by GEJE was estimated to be approximately 10T JPY in Fukushima alone and approximately 100T JPY over the decade.

5. RESULTS

5.1. Production Capacity

Table III shows the production capacity (θ) of 54 industrial sectors in the case of each earthquake (Supplementary Information Figs. S11–S12). For simplicity, this study considers approximately 99% or more to represent a temporary recovery. Values in parentheses denote production capacity after the first temporary recovery.

The production capacities associated with five of the earthquakes, excepting GEJE, are as follows. For H95Jan, production capacity is 84.5% when t=1 (the worst). It recovers (100%) when t=5 which is set to be the reference month; however, it then drops from the sixth month (97.5%) and does not recover to 100% again during the period. For N04Oct, production capacity is 95.8% (t=1) and 95.6% (t=2; the worst), and recovers to 99.4% when t=7. For N07Jul, production capacity is 96.9% (t=1) and recovers to 99.0% (t=2). For IM08Jun, production capacity is 96.7% (t=1) and 95.7% (t=2; the worst). Interestingly, it drops to 92.4% (t=3) and then more severely to 69.6% when t=10, probably because of the global financial crisis in 2008. Thus, as a caveat, the model cannot separate the impact of two or more shocks occurring simultaneously (e.g., a disaster shock and a macroeconomic shock). Finally, regarding K16Apr, production capacity is 76.6% (t=1) and 72.6% (t=2; the worst), and recovers to 99.7% (t=5). From these results, the peak of earthquake damage (to production) tends to occur in the first or second month after the earthquake. As the worst case, K16Apr induced a drop to 72.6% in the second month. Also, importantly, production capacity tends to temporarily recover between the fourth and eighth months after the disaster.

Damage attributable to GEJE differs substantively between FIMIC and non-FIMIC prefectures. Regarding FIMIC, production capacity is lowest at 67.5% (t=1), and indeed this represents a greater impact on capacity than any of the other five earthquakes discussed above. It then gradually improves to 93.4% (t=12; 1 year), and (almost) recovers fully, to 98.9%, in the 37th month (t=37). Thus, the impact of the triple disaster is enormous, and the first temporal recovery took longer to occur than that for the above five earthquakes (mainly because of the damage in Fukushima). Meanwhile, regarding non-FIMIC prefectures, production capacity is lowest at 86.8% (t=1) and recovers to 100.5% (t=8). Therefore, the speed of recovery in these prefectures was similar to that of the above five earthquakes.

5.2. Estimated Results

Tables IV and V show the estimated results of price, which is the weighted average by initial production within the focal prefectures in the 54 manufacturing and mining sectors, and the monthly damage for 12 months, and Table VI summarizes the peak and cumulative damage, which is also calculated only for the focal prefectures in the 54 sectors. In Tables IV and V values in parentheses indicate the periods after the economy recovers temporarily. Figs. 4 and 5 plot the results of price and cumulative loss of SS, respectively (for other damage results, see Supplementary Information Figs. S13–S17).

Regarding the five earthquakes, the price peaks during the first month (the four cases) or second month (IM08Jun) (Fig. 4). H95Jan and K16Apr exhibit the worst increase in price (0.128 and 0.202), whereas N04Oct, N07Jul, and IM08Jun have a relatively small effect on the price by several percent (0.037, 0.028, and 0.033).

Tables V and VI and Fig. 5 represent the loss of SS (Δss) as the ratio of initial production, where the numerator is each of the losses, and the denominator is the initial production value only in the 54 manufacturing and mining sectors in the disaster area. The greatest damage at the peak (Δss) is 18.7% (i.e., 0.187 month-production damage; 0.22T JPY) for H95Jan and 31.6% (0.07T JPY) for K16Apr. 0.22T JPY in H95Jan is larger than 0.07T JPY in K16Apr because the economic scale in Hyogo is larger than Kumamoto. In the other three cases, Δss at the peak is approximately 5% of initial production (5.7% [0.02T JPY] for N04Oct. 4.6% [0.02T JPY] for N07Jul, and 4.8% [0.03T JPY] for IM08Jun). When dividing Δss into losses of CS (Δcs) and PS (Δps), Δss consists almost of Δcs, and Δps tends to be small and even negative (i.e., profit). Specifically, Δcs at the peak are 0.25T JPY (22.1%) for H95Jan, 0.03T JPY (6.6%) for N04Oct, 0.02T JPY (5.1%) for N07Jul, 0.03T JPY (5.6%) for IM08Jun, and 0.07T JPY (33.0%) for K16Apr; similarly, Δps at the peak are −0.03T JPY (−2.4%) for H95Jan, −0.004T JPY (−0.9%) for N04Oct, −0.002T JPY (−0.5%) for N07Jul, −0.004T JPY (−0.8%) for IM08Jun, and −0.003T JPY (−1.4%) for K16Apr.

The damages are likely to converge until the eighth month at most. In Table VI, the cumulative loss of Δss until the temporal recovery is 105.9% (1.25T JPY) in H95Jan (t=12) and 59.0%

(0.13T JPY) in K16Apr (t=7), meaning that the worst earthquake tends to have caused damage of over half a month's worth of production (i.e., more than 50%). The other three cases have lost SS (Δss) by approximately 10–20% until the temporal recovery (21.3% [0.09T JPY] for N04Oct when t=8, 16.4% [0.07T JPY] for N07Jul when t=5, and 7.9% [0.04T JPY] for IM08Jun when t=2).

Meanwhile, GEJE increased the price by 0.279 in FIMIC prefectures at the peak (t=1), which is larger than the worst earthquake (0.202 for K16Apr), and by 0.083 in non-FIMIC prefectures (t=1), which is slightly larger than N04Oct, N07Jul, and IM08Jun (Table V). The loss of SS (Δss) at the peak (Table VI) is 1.35T JPY (43.5%) in FIMIC (where Δcs is 1.46T JPY and Δps is −0.1T JPY) and 2.18T JPY (9.8%) in non-FIMIC (where Δcs is 2.1T JPY and Δps is 0.08T JPY). In addition, the cumulative Δss due to GEJE (Table VI) is 8.05T JPY (251.5%) when t=37 in FIMIC (where Δcs is 8.82T JPY and Δps is −0.77T JPY) and 9.11T JPY (41.1%) when t=8 in non-FIMIC (where Δcs is 9.1T JPY and Δps is 0.01T JPY).

5.3. Discussion

Here, the results are compared with those from Toyoda and Kouchi (1997) for H95Jan and Hayashi (2012) for GEJE (Supplementary Information Table S12). Regarding H95Jan, this study estimates that the damage of SS is 1.25T JPY (where Δcs is 1.45T JPY and Δps is –0.2T JPY). Meanwhile, Toyoda and Kouchi (1997) estimated that indirect damage for one year in the main damaged area in Hyogo was approximately 1,203.1B JPY for industrial sectors. Therefore, the loss of SS estimate from this study is 103.9% (=1.25T/1.2031T) of the indirect damage estimation by Toyoda and Kouchi (1997); therefore, they are approximately equal.

Regarding GEJE, the loss of SS at the first temporary recovery is 7.83T JPY to FIMIC prefectures (t=37) and 9.11T JPY to non-FIMIC prefectures (t=8). Therefore, the damage estimated herein is at least 16.94T JPY (=7.83T+9.11T). Meanwhile, Hayashi (2012) suggested that the indirect damage of GEJE was approximately 100T JPY over 10 years. Roughly estimating the indirect damage incurred only by the industrial sectors gives approximately 24T JPY for 10 years because these sectors produced 24% of the total final demand in 2005. Therefore, the loss of SS estimate of this study is

70.6% (=16.94T/24T) of the indirect damage estimated by Hayashi (2012), which suggests an underestimation. This is probably because of the target periods; this study estimates the first temporal recovery (37 and eight months), whereas Hayashi (2012) considers ten years.

6. CONCLUSIONS

This study examines how to consider the supply constraint in IOA. Different from GPM in Park (2007), this study adopts LPM by introducing the price elasticity of demand, because of the following two points. First, LPM is for supply-side analysis and is suited to the supply constraint. Second, LPM can handle "price" change (Dietzenbacher, 1997). In addition, this study proposes to use the loss of SS as the damage of supply constraint, because, unlike profit (margin), production (sales) does not identify how much damage is passed on to each supplier (upstream sector) and buyer (downstream sector).

Our methodology of the supply constraint is applied to the large earthquakes in Japan. Following the results, implications vis-à-vis countermeasures are as follows. The largest earthquakes tend to require economic assistance for 0.2–0.3 months (of initial production) immediately after a disaster within a damaged prefecture and more than 0.5 months (50% of initial production) in total until the first temporal recovery (the eighth month at most) to compensate for the loss of SS. Also, GEJE required twice as much (fast) economic assistance in the FIMIC prefectures than that required to address the damage caused by the largest earthquakes, which was at least 25 months in total (over 250% of initial production at the 37th month). Meanwhile, non-FIMIC prefectures tended to incur approximately 0.4-month damage (i.e., the loss of SS) until the eighth month. Note that our estimation is similar to (or slightly smaller than) the indirect damage estimation in the literature (Hayashi, 2012; Toyoda and Kouchi, 1997).

Our approach in LPM is straightforward to apply because it requires only a usual MRIO table and production capacity data, with simple assumptions (i.e., the input coefficients are invariant; the price elasticity of demand; and the linear functions of supply and demand). Note, however, that there are the following limitations. Because this study considered the supply constraint, the production capacity in the study is exogenous (based on past data). Therefore, this study does not predict when disaster damage will converge, and does not deal with simulating how to minimize the loss of SS (Supplementary Information D.2). For example, the IOA literature (e.g., Li et al., 2013) often examines these kinds of predictions and simulations, considering disaster countermeasures such as import and export policies, transfer policies among multi-regions, inventory management, and so on. As another limitation, because production capacity is exogenous in the model, the impact of two or more simultaneous shocks cannot be separated (as in the case of IM08Jun). Nevertheless, as easily as the basic IOA, the supply constraint of this study can be applied to indirect damage predictions (or, the loss of SS) of potential catastrophes such as the Nankai Trough earthquakes [Nankai megathrust earthquakes] near Japan, which are anticipated to occur in the future (Investigative Commission for Nankai Trough Earthquake Model, 2012; Working Group on Countermeasures to the Nankai Trough Earthquake, 2012).

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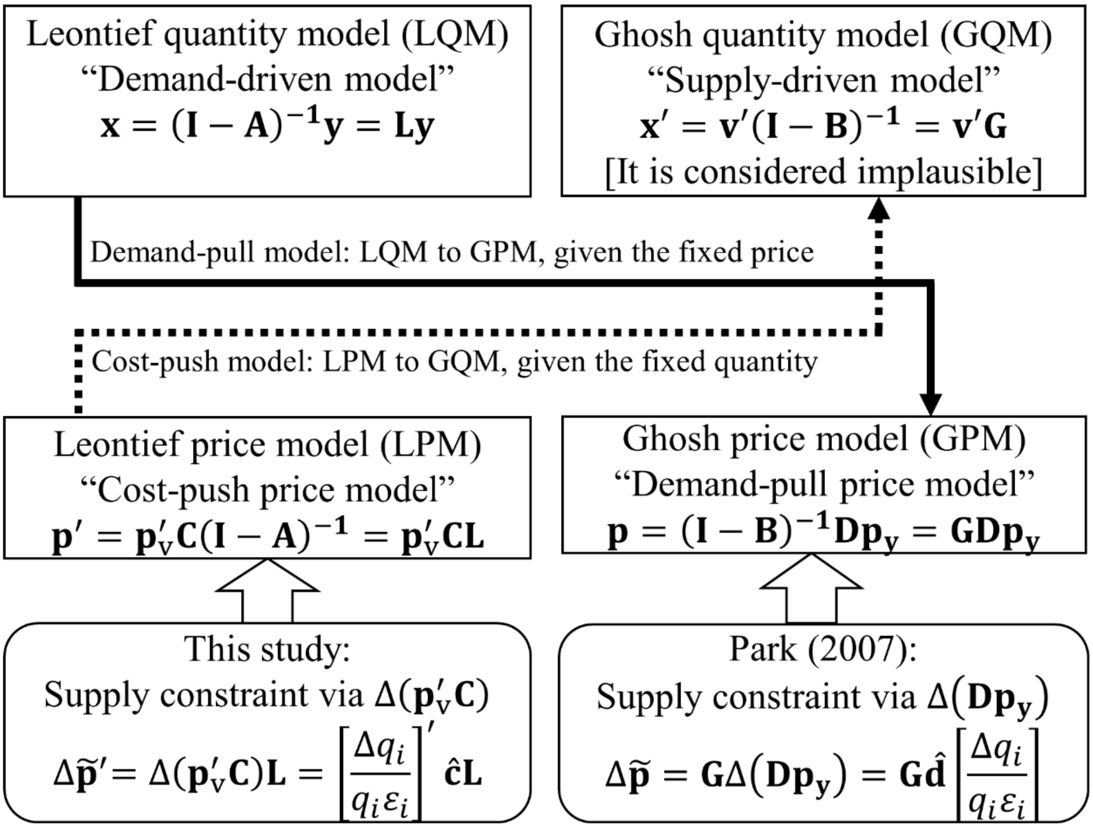

Fig. 1. Leontief and Ghosh models with Park (2007) and this study

Notes: This figure shows the relationship between the four models (LQM, GQM, LPM, and GPM) and the application of supply constraint by Park (2007) and this study. As the demand-pull model, LQM can be converted to GPM, given the price is fixed. Meanwhile, as the cost-push model, LPM can be converted to GQM, given the quantity is fixed. The supply constraints are considered via GPM in Park (2007) and LPM in this study.

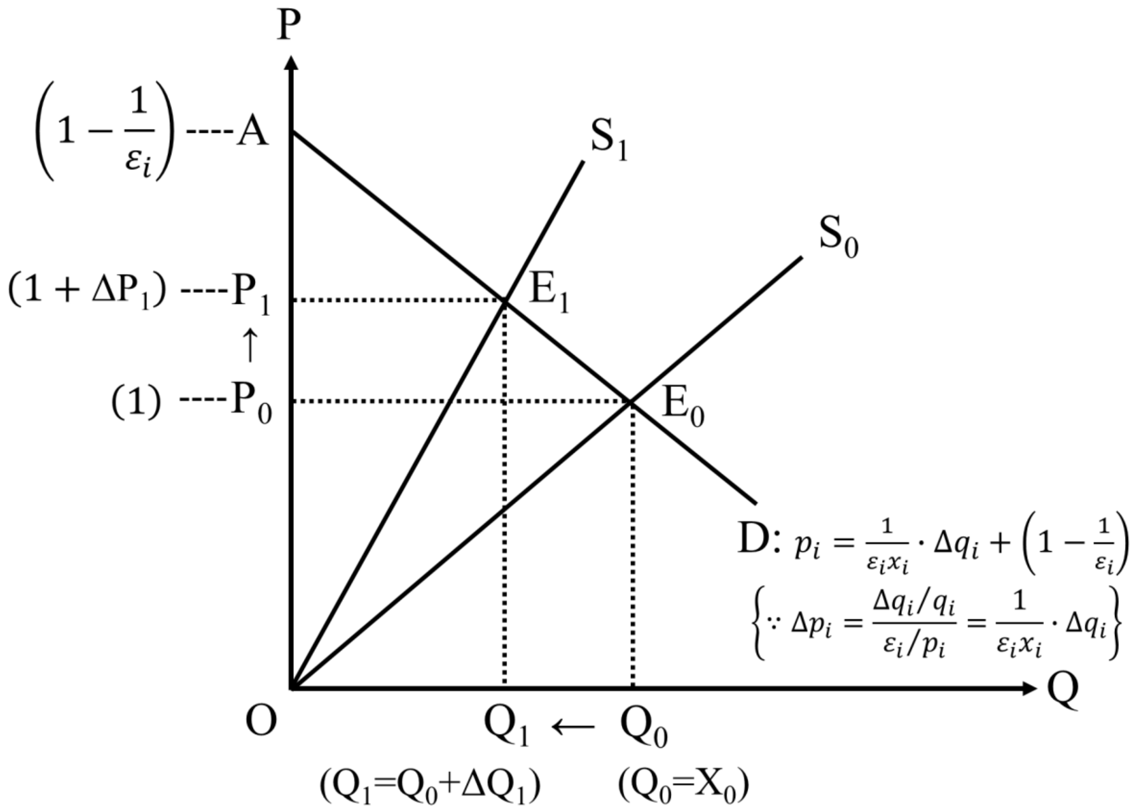

Fig. 2. Demand and supply model with the supply constraint

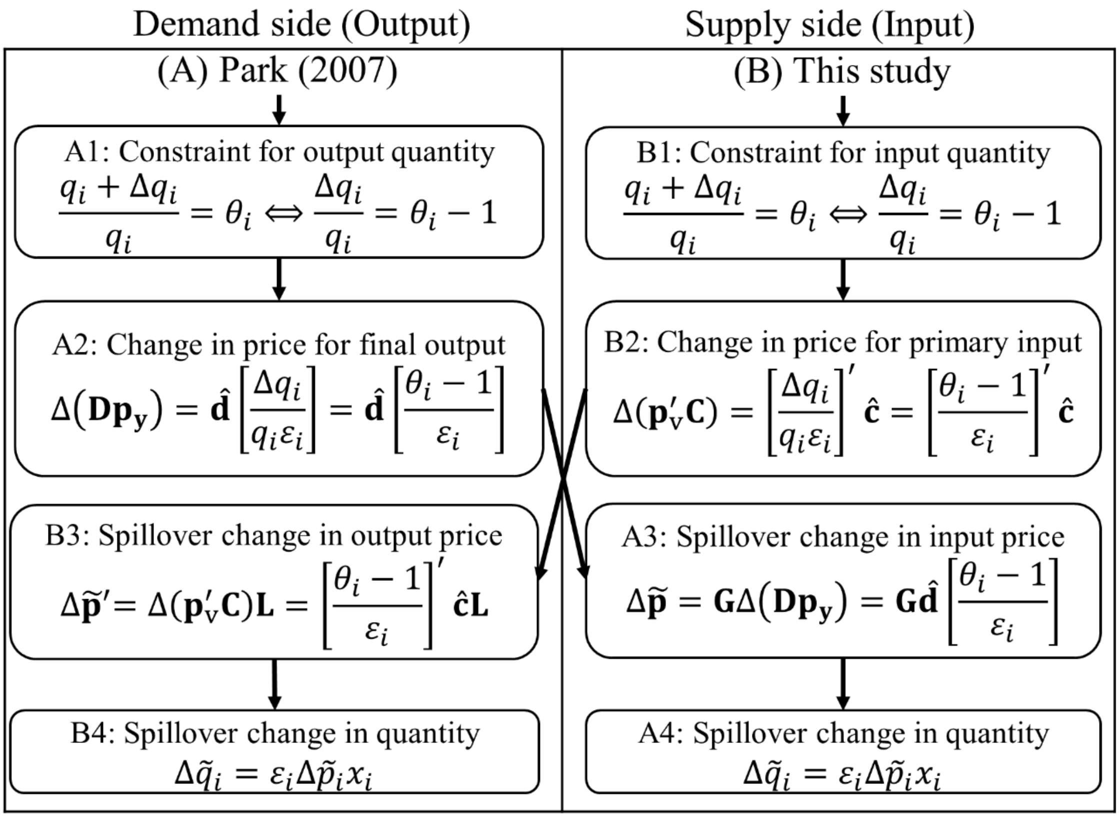

Fig. 3. Difference between Park (2007) and this study

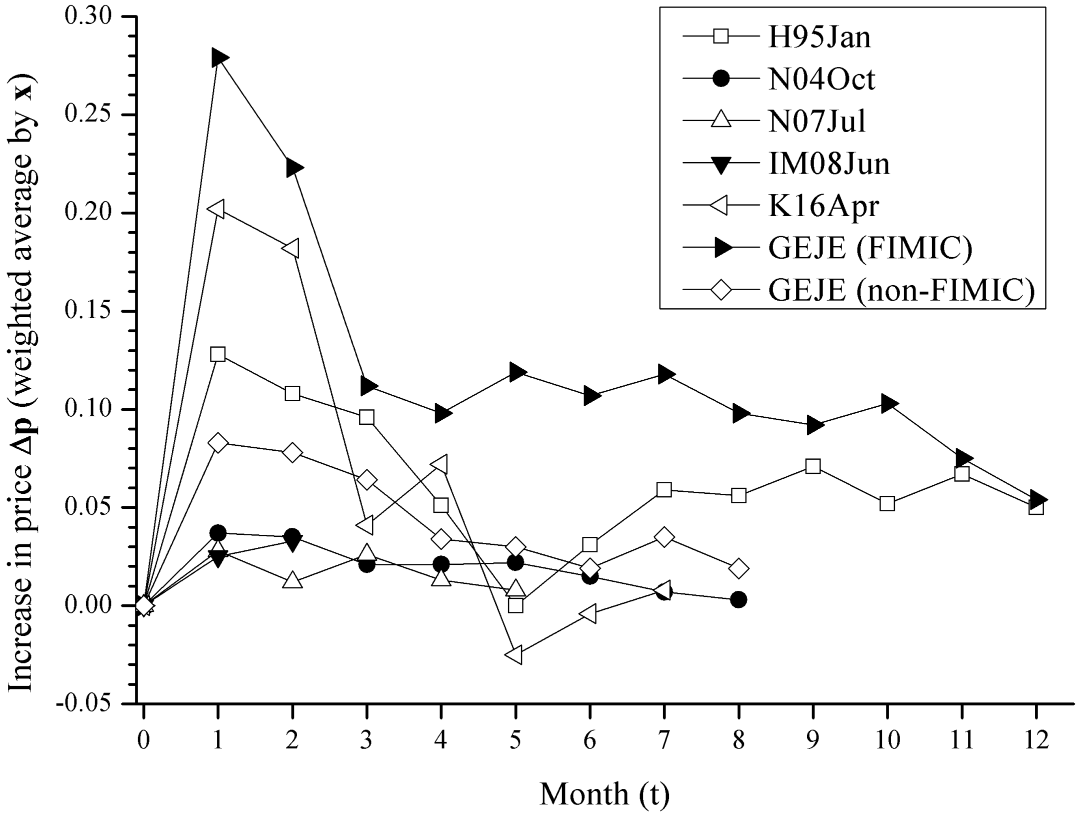

Fig. 4. Increase in price for 12 months (initial price is one)

Notes: Price is one at t=0 and is the weighted average by initial production within the focal prefectures in the 54 manufacturing and mining sectors. See Table IV.

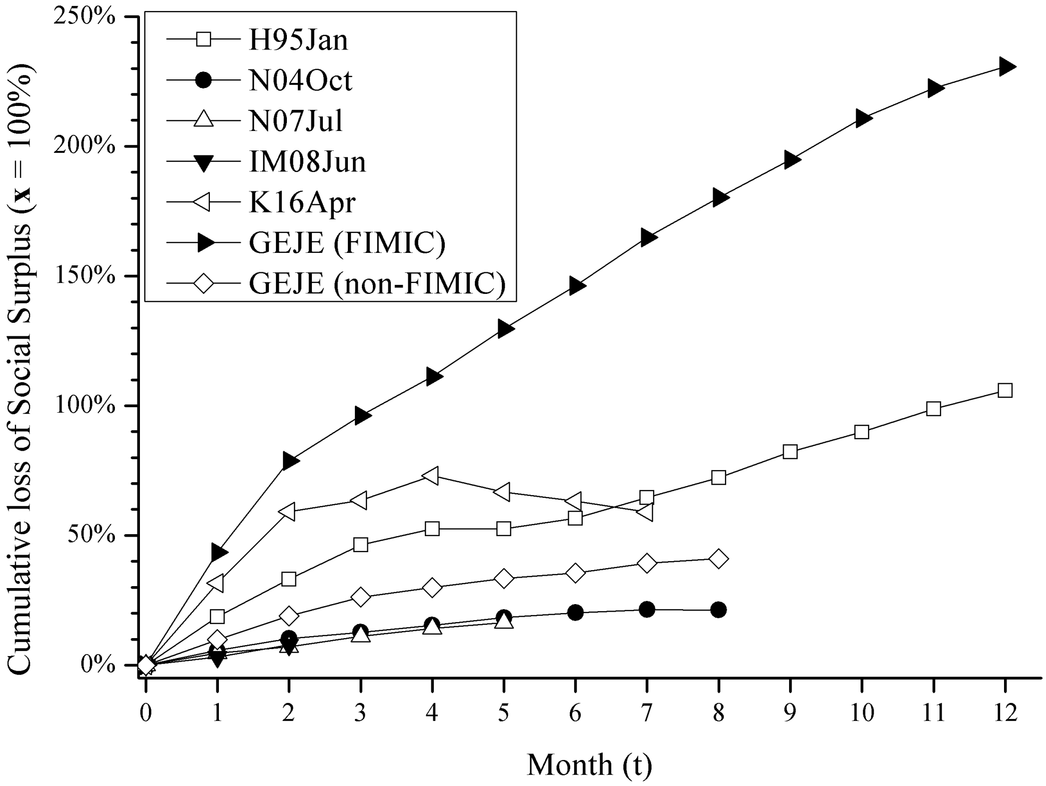

Fig. 5. Cumulative loss of social surplus for 12 months (initial production is 100%)

Note: See Tables V and VI and Supplementary Information Figs. S13–S17.

Table I. Japan's six most destructive earthquakes between 1995 and 2017 and the research settings

#	Date of occurrence	Earthquake name (location)	Human damage	Main Physical damage	Focal prefectures	t=0	t=1
H95Jan	Jan 17, 1995	The Hyogo-ken Nanbu Earthquake (Hanshin region; mainly in Hyogo)	6,434 deaths, 3 missing people, and 43,792 injured people	104,906 and 144,274 houses were completely and partially destroyed	Hyogo	(May 1995)	Jan 1995
N04Oct	Oct 23, 2004	The Mid Niigata Prefecture Earthquake in 2004 (Chuetsu [middle] region of Niigata)	68 deaths and 4,805 injured people	3,175 and 13,810 houses were completely and partially destroyed	Niigata	Sep 2004	Oct 2004
N07Jul	Jul 16, 2007	The Niigata-ken Chuetsu-oki Earthquake in 2007 (Chuetsu offshore of Niigata)	15 deaths and 2,346 injured people	1,331 and 5,710 houses were completely and partially destroyed	Niigata	Jun 2007	Jul 2007
IM08Jun	Jun 14, 2008	The Iwate-Miyagi Nairiku Earthquake in 2008 (southern inland of Iwate Prefecture)	17 deaths, 6 missing people, and 426 injured people	30 and 146 houses were completely and partially destroyed	Iwate and Miyagi	May 2008	Jun 2008
GEJE	Mar 11, 2011	The 2011 off the Pacific coast of Tohoku Earthquake (the Great East Japan Earthquake)	19,630 deaths, 2,569 missing people, and 6,230 injured people	121,781 and 280,962 houses were completely and partially destroyed	Fukushima, Iwate, Miyagi, Ibaraki, and Chiba (FIMIC)	Mar 2016	Apr 2016
K16Apr	Apr 14 to 16, 2016	The 2016 Kumamoto earthquakes (Kumamoto prefecture)	269 deaths and 2,806 injured people	8,668 and 34,716 houses were completely and partially destroyed	Kumamoto	Feb 2011	Mar 2011

Notes: Regarding H95Jan, because there is no data for the month prior to this earthquake (i.e., December 1994), the month before the disaster (t=0) is set as May 1995 because this month exhibited the highest production capacity in that year.

Table II. Price elasticity of demand (weighted by real gross output as of 2005)

#	(1) Elasticity (ε)	(2) Summarized industry group (#1–17)	(3) IIP industry group (#1–80)	(4) JIP industry group (#1–100)
1	–0.450	Mining, food products, textile/chemical fibers, and pulp	2–8,11,12,19	5–16
2	–0.643	Chemical, pharmaceutical, petroleum, and cement products	14–18, 20-23, 26–29	17–28
3	–0.378	Iron, steel, and metal	30–37	29–34
4	–0.395	Machinery and electrical products	38–49	35–48
5	–2.123	Motor vehicles and equipment	50–53	49–51
6	–0.288	Miscellaneous manufacturing industries (printing, plastic, and so on)	9,10,13,24,25,54,55	52–59
7	–0.058	Agriculture	1	1–4
8	–0.087	Utilities and waste disposal	60–62	60–65
9	–2.093	Construction	56–59	66,67,89
10	–1.820	Retail and wholesale	63	68,69
11	–0.072	Transportation and mail	67,77	70–75, 88
12	–1.879	Communications and information services	68–72,76	78–81,87
13	–0.813	Finance and insurance	64	82,83
14	–1.104	Housing and real estate	65,66	76,84,85
15	–3.270	Medical service	75	93–95
16	–2.987	Research, education, and other services for businesses	73,74,78	86,90–92
17	–0.414	Other services for individuals	79,80	77,96–100
1–17	–1.305	Total sectors	1–80	1–100
1–6	–0.717	Manufacturing and mining sectors	5–59	2–55
7–17	–1.598	Agriculture and service sectors	1–4.60–80	1,56–100

Notes: This table shows the price elasticity of demand at the weighted average value by using the real gross output (as of 2005). Columns 1 and 2 show the summarized 17 industry groups and their elasticity (ε). Columns 3 and 4 indicate the JIP Industry group (#1–100) and IIP Industry group (#1–80), respectively, to connect with the summarized industry groups (#1–17). See Supplementary Information Tables S10 and S11 for the descriptive statistics and the regression results.

Table III. Production capacity (θ)

t (months)	H95Jan	N04Oct	N07Jul	IM08Jun	K16Apr	GEJE (FIMIC)	GEJE (non-FIMIC)
0 (B JPY)	100.0% (1,179B)	100.0% (400B)	100.0% (400B)	100.0% (525B)	100.0% (226B)	100.0% (3,114B)	100.0% (22,150B)
1	84.5%	95.8%	96.9%	96.7%	76.6%	67.5%	86.8%
2	87.1%	95.6%	99.0%	95.7%	72.6%	72.7%	87.2%
3	89.1%	96.9%	97.5%	(92.4%)	91.6%	86.7%	91.3%
4	94.9%	97.2%	99.2%	(92.9%)	87.9%	89.3%	96.3%
5	100.0%	97.2%	99.6%	(92.3%)	99.7%	85.8%	97.3%
6	97.5%	98.2%	(100.5%)	(84.0%)	98.9%	87.7%	98.7%
7	94.1%	99.4%	(98.8%)	(76.6%)	99.6%	85.0%	97.6%
8	95.3%	99.8%	(99.4%)	(74.5%)	(106.3%)	88.4%	100.5%
9	91.2%	(98.6%)	(98.6%)	(69.8%)	(106.8%)	89.2%	(96.9%)
10	95.7%	(100.1%)	(98.0%)	(69.6%)	(106.2%)	87.1%	(99.9%)
11	93.1%	(101.2%)	(99.1%)	(75.6%)	(111.8%)	90.9%	(100.6%)
12 (1 year)	95.0%	(99.7%)	(99.0%)	(76.9%)	(113.2%)	93.4%	(101.3%)
37	—	—	—	—	—	98.9%	(101.6%)
48 (4 years)	—	—	—	—	—	(95.7%)	(98.7%)

Notes: Production capacity is set to 100% before a disaster (t=0). Regarding H95Jan, because there is no data for the month prior to this earthquake (i.e., December 1994), the month before the disaster (t=0) is set as May 1995 (the highest production capacity for the 12 months). Regarding IM08Jun, production capacity further decreases from the third month, probably because of the global financial crisis in 2008. See Supplementary Information Figs. S11–S12.

Table IV. The change in output price (Δp)

t (months)	H95Jan	N04Oct	N07Jul	IM08Jun	K16Apr	GEJE (FIMIC)	GEJE (non-FIMIC)
1	0.128	0.037	0.028	0.025	0.202	0.279	0.083
2	0.108	0.035	0.012	0.033	0.182	0.223	0.078
3	0.096	0.021	0.026	(0.059)	0.041	0.112	0.064
4	0.051	0.021	0.013	(0.051)	0.072	0.098	0.034
5	0.000	0.022	0.008	(0.054)	−0.025	0.119	0.030
6	0.031	0.015	(0.003)	(0.116)	−0.004	0.107	0.019
7	0.059	0.007	(0.024)	(0.171)	0.008	0.118	0.035
8	0.056	0.003	(0.021)	(0.188)	(−0.059)	0.098	0.019
9	0.071	(0.014)	(0.026)	(0.214)	(−0.072)	0.092	(0.036)
10	0.052	(0.002)	(0.033)	(0.220)	(−0.086)	0.103	(0.021)
11	0.067	(−0.014)	(0.026)	(0.182)	(−0.117)	0.075	(0.015)
12 (1 year)	0.050	(0.010)	(0.025)	(0.171)	(−0.111)	0.054	(0.013)
37	—	—	—	—	—	0.008	(0.007)
48 (4 years)	—	—	—	—	—	(0.043)	(0.037)

Notes: Price is one at t=0 and is the weighted average by initial production within the focal prefectures in the 54 manufacturing and mining sectors. Values are in parentheses after the first temporal recovery (except for IM08Jun; see Results). See Fig. 4.

Table V. The losses of social, consumer, and producer surpluses (compared with the initial monthly production)

t (months)	H95Jan	N04Oct	N07Jul	IM08Jun	K16Apr	GEJE (FIMIC)	GEJE (non-FIMIC)
Initial production (**x**) in manufacturing sectors (T JPY)	1.2T (100%)	0.4T (100%)	0.4T (100%)	0.5T (100%)	0.2T (100%)	3.1T (100%)	22.1T (100%)
Loss of social surplus (Δss)							
1 month	18.7%	5.7%	4.6%	3.1%	31.6%	43.5%	9.8%
2	14.3%	4.7%	2.4%	4.8%	27.5%	35.2%	9.2%
3	13.3%	2.3%	4.2%	(9.7%)	4.3%	17.5%	7.2%
4	6.2%	2.7%	2.9%	(8.1%)	9.5%	15.1%	3.7%
5	0.0%	2.9%	2.3%	(9.3%)	−6.3%	18.4%	3.4%
6	4.0%	2.0%	(1.4%)	(18.6%)	−3.5%	16.6%	2.1%
7	8.0%	1.1%	(4.7%)	(28.4%)	−4.2%	18.6%	3.8%
8	7.7%	−0.1%	(4.6%)	(30.9%)	(−16.5%)	15.4%	1.8%
9	9.9%	(1.3%)	(5.4%)	(35.0%)	(−16.2%)	14.5%	(3.7%)
10	7.6%	(−0.1%)	(7.0%)	(35.8%)	(−17.7%)	16.0%	(2.2%)
11	9.1%	(−2.6%)	(6.6%)	(30.1%)	(−24.8%)	11.5%	(1.5%)
12 (1 year)	7.0%	(1.0%)	(5.9%)	(28.4%)	(−22.4%)	8.4%	(1.4%)
37	—	—	—	—	—	1.1%	(0.6%)
48 (4 years)	—	—	—	—	—	(7.1%)	(4.5%)
Loss of consumer surplus (Δcs)							
1 month	21.1%	6.6%	5.1%	3.7%	33.0%	46.7%	9.5%
2	17.0%	5.7%	2.5%	5.6%	28.4%	37.7%	8.6%
3	15.4%	3.2%	4.6%	(10.8%)	4.3%	19.1%	7.1%
4	7.6%	3.5%	2.9%	(9.3%)	9.1%	16.7%	3.8%
5	0.0%	3.5%	2.2%	(10.3%)	−8.1%	20.4%	3.6%
6	4.9%	2.5%	(1.0%)	(21.0%)	−4.8%	18.5%	2.1%
7	9.3%	1.4%	(4.6%)	(31.6%)	−4.9%	20.6%	4.2%
8	8.9%	0.3%	(4.3%)	(34.2%)	(−19.5%)	17.2%	2.2%
9	11.3%	(2.0%)	(5.2%)	(38.4%)	(−19.9%)	16.1%	(3.7%)
10	8.8%	(0.2%)	(6.6%)	(39.2%)	(−22.9%)	18.0%	(2.3%)
11	10.5%	(−2.8%)	(6.4%)	(32.9%)	(−30.4%)	13.1%	(1.7%)
12 (1 year)	8.0%	(1.5%)	(5.5%)	(30.9%)	(−25.7%)	9.5%	(1.6%)
37	—	—	—	—	—	0.8%	(0.2%)
48 (4 years)	—	—	—	—	—	(7.2%)	(4.5%)
Loss of producer surplus (Δps)							

1 month	−2.4%	−0.9%	−0.5%	−0.6%	−1.4%	−3.3%	0.4%
2	−2.6%	−1.0%	−0.1%	−0.8%	−0.8%	−2.4%	0.6%
3	−2.0%	−0.9%	−0.5%	(−1.1%)	0.0%	−1.6%	0.1%
4	−1.4%	−0.7%	0.0%	(−1.2%)	0.4%	−1.6%	0.0%
5	0.0%	−0.7%	0.0%	(−1.1%)	1.8%	−2.0%	−0.1%
6	−0.8%	−0.5%	(0.3%)	(−2.4%)	1.3%	−1.9%	0.0%
7	−1.4%	−0.3%	(0.1%)	(−3.2%)	0.6%	−2.1%	−0.4%
8	−1.2%	−0.4%	(0.3%)	(−3.3%)	(3.1%)	−1.8%	−0.4%
9	−1.4%	(−0.7%)	(0.2%)	(−3.4%)	(3.7%)	−1.6%	(0.0%)
10	−1.2%	(−0.3%)	(0.3%)	(−3.4%)	(5.2%)	−2.0%	(−0.2%)
11	−1.4%	(0.2%)	(0.2%)	(−2.8%)	(5.5%)	−1.5%	(−0.2%)
12 (1 year)	−1.0%	(−0.4%)	(0.4%)	(−2.6%)	(3.3%)	−1.2%	(−0.2%)
37	—	—	—	—	—	0.3%	(0.5%)
48 (4 years)	—	—	—	—	—	(−0.1%)	(0.0%)

Notes: Initial monthly production (at t=0) is 100%. Values are in parentheses after the first temporal recovery (except for IM08Jun). Note that these values are calculated only for the focal prefectures in the 54 sectors. See Fig. 5 for cumulative Δss and Supplementary Information Figs. S11–S15 for Δss, Δcs, and Δps.

Table VI. Values at the peak and cumulative summation at the temporal recovery

	H95Jan	N04Oct	N07Jul	IM08Jun	K16Apr	GEJE (FIMIC)	GEJE (non-FIMIC)
Initial production (**x**) in manufacturing sectors (T JPY)	1.2T (100%)	0.4T (100%)	0.4T (100%)	0.5T (100%)	0.2T (100%)	3.1T (100%)	22.1T (100%)
Δp at the peak (The peak month)	0.128 (t=1)	0.037 (t=1)	0.028 (t=1)	0.033 (t=2)	0.202 (t=1)	0.279 (t=1)	0.083 (t=1)
Δss at the peak (T JPY) (**x**=100%)	0.22T (18.7%)	0.02T (5.7%)	0.02T (4.6%)	0.03T (4.8%)	0.07T (31.6%)	1.35T (43.5%)	2.18T (9.8%)
Δcs at the peak (T JPY) (**x**=100%)	0.25T (22.1%)	0.03T (6.6%)	0.02T (5.1%)	0.03T (5.6%)	0.07T (33.0%)	1.46T (46.7%)	2.10T (9.5%)
Δps at the peak (T JPY) (**x**=100%)	−0.03T (−2.4%)	−0.004T (−0.9%)	−0.002T (−0.5%)	−0.004T (−0.8%)	−0.003T (−1.4%)	−0.1T (−3.3%)	0.08T (0.4%)
(The temporal recovery)	(t=12)	(t=8)	(t=5)	(t=2)	(t=7)	(t=37)	(t=8)
Cumulative Δss (T JPY) (**x**=100%)	1.25T (105.9%)	0.09T (21.3%)	0.07T (16.4%)	0.04T (7.9%)	0.13T (59.0%)	8.05T (251.5%)	9.11T (41.1%)
Cumulative Δcs (T JPY) (**x**=100%)	1.45T (122.9%)	0.11T (26.8%)	0.07T (17.4%)	0.05T (9.3%)	0.13T (57.0%)	8.82T (283.4%)	9.1T (41.1%)
Cumulative Δps (T JPY) (**x**=100%)	−0.2T (−17.0%)	−0.02T (−5.5%)	−0.004T (−1.0%)	−0.01T (−1.4%)	0.004T (1.9%)	−0.77T (−24.8%)	0.01T (0.1%)

Notes: Price is one at t=0 and is the weighted average by initial production within the focal prefectures in the 54 manufacturing and mining sectors. Initial monthly production (at t=0) is 100%. See Tables IV and V.

Supplementary Information

Abstract

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Abbreviations

- B: billion
- CGE: computable general equilibrium
- CS: consumer surplus
- FIDELIO: Fully Interregional Dynamic Econometric Long-term IO
- FIMIC: Fukushima, Iwate, Miyagi, Ibaraki, and Chiba
- GDP: gross domestic product
- GEJE: the Great East Japan Earthquake (GEJE)
- GPM: the Ghosh price model
- GQM: the Ghosh quantity model
- H95Jan: the Hyogo-ken Nanbu Earthquake in January 1995
- ICFM: integrated commodity flow model
- IIP: indices of industrial production
- IM08Jun: the Iwate-Miyagi Nairiku Earthquake in June 2008
- IO: input-output
- IOA: input-output analysis
- JIP: Japan Industrial Productivity
- JPY: Japanese yen
- K16Apr: the 2016 Kumamoto earthquakes in April 2016
- LPM: the Leontief price model
- LQM: the Leontief quantity model
- MB: million barrels
- MRIO: multi-regional input-output
- N04Oct: the Mid Niigata Prefecture Earthquake in October 2004
- N07Jul: the Niigata-ken Chuetsu-oki Earthquake in July 2007
- PS: producer surplus
- SAM: social accounting matrix
- SIM: Sequential Interindustry Model
- SS: social surplus
- T: trillion
- USD: U.S. dollar
- $/B: U.S. dollars per barrel

Supplementary Information A: Implausibility of GQM

In the IO literature, Oosterhaven (1988) has argued that GQM is implausible and has concluded that "both as a general description of the working of any economy and as a way to estimate the effects of loosening or tightening the supply of one scarce resource, the supply-driven model may not be used" (Oosterhaven, 1988, p.208). In GQM, the delivery from primary input ($\Delta\mathbf{v}$) to final demand ($\mathbf{y}$) is possible without any intermediate input, labor, and capital.

By using the Taylor expansion as in Oosterhaven (1988, Fig. 1 in p.206 and Eq.12 in p.207; Supplementary Information Fig. S1), GQM (Eq.10) is solved:

$$\mathbf{x}' = \mathbf{v}'\mathbf{I} + \mathbf{v}'\mathbf{B} + \mathbf{v}'\mathbf{B}^2 + \mathbf{v}'\mathbf{B}^3 + \cdots \tag{S1}$$

First, it is assumed the primary input is increased only in sector i (Δv_i) but not others (i.e., zero). The first term of the series ($\mathbf{v}'\mathbf{I}$) is the direct increase of this new production (e.g., extra input of \$100 in sector i). Because it is direct, it is possible without any intermediate inputs. Next, the second term of the series ($\mathbf{v}'\mathbf{B}$) is the first round indirect (forward-linkage) production effects of the direct production effect in sector i. This means that the additional increase in production in sector i (e.g., \$100 times $\mathbf{B}$) is purchased by i and other sectors (as their inputs). Importantly, this is possible without any intermediate input and any increase in labor and capital. This interpretation applies to the third term ($\mathbf{v}'\mathbf{B}^2$) and others as well, and these round effects (i.e., endogenous forward production effect) are assumed to be finished simultaneously. Thus, these round effects are possible without any intermediate input, labor, and capital, and they will at last increase the final demand.

Supplementary Information B. Review of Park (2009)

This part reviews Park (2009; the unpublished paper). Park (2009) is helpful for understanding Park's (2007) approach and also beneficial as an example study of the price IO model in the U.S. oil industry because the price IO model has much fewer applications than the quantity model. Following Park's (2007) approach, Park (2009) examined the economic losses in the U.S. oil industry caused by two hurricanes (Katrina and Rita, which occurred in August 2005). After the two hurricanes hit the Gulf of Mexico coast (Louisiana and surrounding areas), the proportion of U.S. mining production in the state of Louisiana decreased from 11,090 million U.S. dollars (USD) in 2004 (10.23% of the U.S. total) to 9,569 million USD in 2005 (9.06% of the U.S. total) (i.e., it was changed by −13.72%). Park (2009) created the national IO table with 47 USC sectors (29 commodity sectors and 18 service sectors) and estimated the economic losses due to the damage in the U.S. oil industry for the four months after the hurricanes. Note that Park, Son, & Park (2017) recently examined the economic losses (job losses) caused by hurricane Sandy, which occurred in 2012, for U.S. industry. Park et al. (2017) also use the same 47 USC sectors, which are converted from the two-digit North American Industry Classification System sectors.

The model of Park (2009) is simplified as follows. From Eq.34 (A1 in Fig. 2), the price elasticity of demand in the oil industry (ε_{oil}) is defined as:

$$\varepsilon_{oil} = \frac{\Delta q_{oil}/q_{oil}}{\Delta p_{oil}/p_{oil}} \tag{B1}$$

Before the hurricanes, the base price of the oil industry (p_{oil}) is set as one, and the quantity of oil products (q_{oil}) is equal to production (x_{oil}). From Eq.35, using the exogenous price elasticity ($\bar{\varepsilon}_{oil}$), the price change is elastic to the quantity change as follows:

$$\Delta p_{oil} = \frac{\Delta q_{oil}/q_{oil}}{\bar{\varepsilon}_{oil}/p_{oil}} = \frac{\Delta q_{oil}}{q_{oil}\bar{\varepsilon}_{oil}} = \Delta q_{oil}\pi_{oil} \tag{B2}$$

where $\pi_{oil} = \frac{p_{oil}}{q_{oil}\bar{\varepsilon}_{oil}} = \frac{1}{q_{oil}\bar{\varepsilon}_{oil}}$. From Eqs. 22 and 38 (A3 in Fig. 2), the spillover change in price ($\Delta\tilde{\mathbf{p}}$) is calculated as:

$$\Delta\tilde{\mathbf{p}} = \mathbf{G}\Delta(\mathbf{D}\mathbf{p}_{\mathbf{y}}) = \mathbf{G}\hat{\mathbf{d}}[\Delta p_{oil}] = \mathbf{G}\hat{\mathbf{d}}[\Delta q_{oil}\pi_{oil}] \tag{B3}$$

$[\Delta p_{oil}]$ means the vector that takes Δp_{oil} in the oil industry and 0 in other industries. Note that Park (2007; 2009) calls the above equations the supply-driven model.

Table S1 shows a summary of the data necessary to estimate the total output vectors (Park, 2009,

Table 3). Note that this table can be calculated without the IO model. The quantity (q_{oil}) was originally expected to be 487.7 million barrels (MB), and the decrease (Δq_{oil}) was -140MB during the proceeding four months (i.e., it changed by -28.7%). The symbol "W" is the weight of each oil product, depending on the decrease proportion in quantity (Δq_{oil}). Note that the weighted average of the oil price before the hurricanes (based on W) would be 63.9 U.S. dollars per barrel ($/B). By using W and $\bar{\varepsilon}_{oil}$, Park (2009) calculated that the price increase (Δp_{oil}) was 5.1534 $/B (an increase of 8.06%). Note that Park (2009) refers to 5.1534 $/B as the total price-type direct losses on the U.S. oil market due to the two hurricanes. Park (2009) also estimated that the total loss in value was $721.5 million for four months, or 140MB (Δq_{oil}) times 5.1534$/B ($\Delta p_{oil}$) (Fig. S2).

Applying the data to the model, Table S1 (Park, 2009, Table 4) shows the estimated results in each of the 47 industries. Park (2009) estimated that the total price increased by 10.9780 $/B where 7.1545 $/B in the oil industry (i.e., USC sector 10: coal and petroleum products) plus 3.8235 $/B sums up the price changes in the other 46 USC industries. Thus, Park (2009) concluded that the total economic losses would be $1.54 billion (i.e., 11$/B times 140MB) (Fig. S2).

As mentioned in the main text, however, this study argues that Park (2009) has some interpretation issues. First, although Park (2007; 2009) calls the approach (Eqs. B1–B3) a supply-driven model, it seems indeed to be a demand-driven model (Section 3.2) because Eq.B3 is based on GPM (the demand-pull price model; Eqs.22 and 32), not on LPM (the cost-push price model; Eqs.15 and 27). Specifically, Δp_{oil} in Eq.B3 is the price change for the final output (final demand) in GPM, not for the value added in LPM. In other words, Eq.B3 treats the drop in 140MB of oil products not as a reduction in the primary inputs (supply) but as a reduction in buyers' purchases (demand). In addition, as in Section 3.5, when we follow Dietzenbacher (1997), GPM is a quantity model (Eqs.19–22) and therefore, cannot handle price changes. Indeed, unlike Dietzenbacher (1997), Eq.B3 treats the vector of price change $[\Delta p_{oil}]$.

Second, Park (2009, Table 4) summed up the price increases in each industry (Table S2). However, this study wonders whether the price vectors should not be summed up for the different industries. For example, suppose that two different industries increase total prices by 0.1 and 0.2 (10% and 20%), respectively. Park's (2009) approach sums them up to 0.3 (30%=10%+20%). Because the two industries do not necessarily have the same price unit, however, the value of 0.3 doesn't seem to make any sense.

Finally, suppose that the following estimation is correct: Δq_{oil} is 140MB, Δp_{oil} is 5.1534$/B, and $\Delta\tilde{\mathbf{p}}$ is 10.9780 $/B. Even so, it seems strange to estimate the total value of losses as $721.5 million (5.1534$/B times 140MB) and the total economic losses as $1.54 billion (10.9780 $/B times 140 MB). Regarding the former, for buyers, 140MB were not purchased (or demanded), and only 347.7MB were indeed purchased at the 5.1534$/B higher price (Fig. S2); therefore, we wonder why the unpurchased 140MB would lose 5.1534$/B (in each deal). Similarly, regarding the latter, for sellers, 140MB were not produced (or supplied), and only 347.7 MB were produced at the 10.9780 $/B higher price (Fig. S2); therefore, we wonder why the non-produced 140 MB lost 10.9780 $/B in each production. In addition, it is important to note that 10.9780 $/B is not necessarily a loss for producers because some percentage of the 10.9780 $/B may be profitable for them (as value added or profit).

From another perspective (as in Section 3.3), we can compare the changes in production (sales) before and after the hurricanes. If there were no hurricanes, sales would have been $31.1 billion, or 487.7MB (q_{oil}) times 63.9$/B ($p_{oil}$). After the hurricanes (347.7MB), sales were $24 billion when the price increased by 5.1534$/B (347.7MB times 69.1$/B) and $26 billion when the price increased by 10.9780$/B (347.7MB times 74.9$/B). Thus, taking the difference without and with the hurricanes, the changes in sales are $−7,154 billion and $−5,129 billion. These values seem much higher than Park's (2009) damage estimate ($721.5 million and $1.54 billion) because the arc price elasticity of oil products is quite low (Section 3.3). After all, the quantity was changed by −28.7% (from 487.7MB to 347.7MB), but the price was increased only by 8.1% (+5.1534$/B from 63.9$/B) and 17.2% (+10.9780$/B). In other words, if the arc elasticity is stronger than 1.4 (i.e., 40.3% divided by –28.7%), sales could even be said to increase after the hurricanes. For example, when the price increases to 89.6 $/B (i.e., increased by 40.3%), the sales after the hurricanes would be the same as before (i.e., $31 billion).

References

Park, J., Son, M., & Park, C. (2017). Natural disasters and deterrence of economic innovation: a case of temporary job losses by Hurricane Sandy. *Journal of Open Innovation: Technology, Market, and Complexity*, *3*(1), 5. doi:10.1186/s40852-017-0055-2

Supplementary Information C: Comparison between IOA, this study (and Park (2007)), and CGE

This study briefly compares the common IOA, this study (and Park (2007)), and CGE (Supplementary Information Table S3). In IOA, price and quantity are usually independent of each other. IOA covers intermediate demand and input (as endogenous sectors), and final demand and value added (as exogenous sectors) (for IO table in this study, see Supplementary Information Fig. S3). The endogenous sectors balance supply and demand (hence, a square matrix) and are endogenous based on the technical coefficients (**A** or **B**). The exogenous sectors do not usually balance supply and demand (hence, it is not a square matrix). Because they are exogenous, labor and capital (as value added) are free to use, whereas household and export (etc.) in final demand are free to change. Also, the basic IOA requires only an IO table. Importantly, IOA is calculated by spreadsheet and has scalability in the calculation (i.e., it does not matter how many sectors are included).

This study (and Park (2007)) adopt IOA, assuming that price is elastic to quantity. The quantity of supply is exogenous (i.e., supply constraint), and the price is endogenous by using the price elasticity of demand. Thus, this study requires some parameters for the supply constraint and the price elasticity of demand. The other assumptions are the same as IOA.

Meanwhile, the CGE models are theoretically consistent. Price and quantity in CGE are theoretically elastic with each other. CGE can identify all economic activities by each of the utility functions. Instead of the IO table, CGE uses a social accounting matrix (SAM). Unlike the IO table, supply and demand in SAM are fully balanced in all economic sectors (hence, SAM is a square matrix; see Supplementary Information Figs. S4 for an example of the IO table and S5 for SAM).

CGE looks ideal for the disaster analysis, but it is harder to estimate than IOA. Regarding the data, CGE requires SAM. Hence, researchers have to create SAM, which covers a broader range than the IO table, and usually need to fit SAM to the CGE model. Also, it is necessary to prepare models (utility functions) and parameters for all activities to be consistent theoretically through the model. In addition, CGE is computable but highly non-linear and has no scalability, meaning that the more sectors there are, the more difficult it is to solve.

Supplementary Information D. Applications to the approaches in the previous studies

D.1 Introduction: The round effects of LQM and LPM

Some readers (including an anonymous reviewer) may wonder how this study relates to the methods proposed in previous studies. Thus, this section briefly discusses the following seven items: the endogenous recovery for the survival coefficient (Section D.2), the sequential interindustry models (SIM) in Romanoff (1984) and Okuyama et al. (2004) (D.3), the impact on transportation networks in Sohn et al. (2004) and Kim et al. (2002) (D.4), the input-occupancy-output model in Chen (1990) and Chen et al. (2005) (D.5), the extension to the CGE model: Fully Interregional Dynamic Econometric Long-term IO (FIDELIO) model in Kratena et al. (2013; 2017) and Kratena and Streicher (2017) (D.6), spatial substitution and price multipliers: the FIDELIO model in Kratena and Streicher (2017) (D.7), and the supply constraints in GQM (D.8).

Before coming to that, this part confirms once again that there is a difference between the LQM (the demand-driven quantity model) and this study based on LPM (the supply-driven price model) because most of the previous researches are based on LQM. First of all, regarding quantity, LQM is suitable for analyzing how the demand (final demand as output; $\mathbf{y}$) causes the supply (production as input; $\mathbf{x}$); however, going the opposite way (from supply to demand) is not suitable. Meanwhile, regarding price, LPM is suitable for analyzing how the supply (value added; $\mathbf{p_v}$) affects the demand ($\mathbf{p}$); similarly, however, going the opposite way (from demand to supply) is not suitable.

Opposite to GQM (from supply to demand, as in Fig. S1), LQM examines an economic effect from the demand (the right) to the supply (the left) only at the quantity level (see Fig. S6). By using the Taylor expansion as in Oosterhaven (1988), LQM (Eq.3) is solved:

$$\mathbf{x} = \mathbf{I}\mathbf{y} + \mathbf{A}\mathbf{y} + \mathbf{A}^2\mathbf{y} + \mathbf{A}^3\mathbf{y} + \cdots \tag{D1.1}$$

First, it is assumed the final demand (final output) is changed only in sector i (Δy_i) but not in others (i.e., zero). The first term of the series ($\mathbf{I}\mathbf{y}$) is the direct increase of this new demand (e.g., the extra output of $100 in sector i). Next, the second term of the series ($\mathbf{A}\mathbf{y}$) is the first round indirect (backward-linkage) production effects of the direct production effect in sector i. This means that the additional increase in production in sector i (e.g., $\mathbf{A}$ times $100) is required by i and other sectors as their outputs. This interpretation applies to the third term ($\mathbf{A}^2\mathbf{y}$) and others as well, and these round effects (i.e., the endogenous backward production effect) are assumed to be finished simultaneously. Thus, they will at last increase the value added (e.g., n-th factor in sector j via the coefficient c_{nj}; Δv_{nj}).

Meanwhile, similarly to GQM, LPM examines an economic effect from the supply (the left) to the demand (the right) at the price level (i.e., the straight arrows in Fig. S7). Note that, as in the dotted arrows in Fig. S7, this study converts the quantity change to a price change (or vice versa), introducing the price elasticity of demand (Park, 2007). Specifically, first, suppose that a certain amount of quantity (as total input) in sector i decreases on the supply side ($\Delta x_i = \Delta q_i$). Note that, instead of Δq_i, Eq.36 uses the survival coefficient θ_i. By using the price elasticity (ε_i), Δq_i is converted to the price change for the value added (primary inputs) of the n-th factor (i.e., $\Delta(p_{vn}c_{ni})$; Eq.37) where c is the (fixed) coefficient for p_v.

By using the Taylor expansion as in Oosterhaven (1988), LPM (Eq.6) is solved:

$$\mathbf{p}' = \mathbf{I}(\mathbf{p}'_{\mathrm{v}}\mathbf{C}) + \mathbf{A}(\mathbf{p}'_{\mathrm{v}}\mathbf{C}) + \mathbf{A}^2(\mathbf{p}'_{\mathrm{v}}\mathbf{C}) + \mathbf{A}^3(\mathbf{p}'_{\mathrm{v}}\mathbf{C}) + \cdots \tag{D1.2}$$

where **C** is the matrix of the coefficient c_{ni}. Similarly to Eq.D1.1, it is assumed the price of value added (primary inputs) is increased only in sector i ($\Delta p_{vn}c_{ni}$) but not others (i.e., zero). The first term of the series ($\mathbf{I}(\mathbf{p}'_{\mathrm{v}}\mathbf{C})$) is the direct increase of this new supply (e.g., extra price margin of one cent per \$1 [1%] in sector i). Next, the second term of the series ($\mathbf{A}(\mathbf{p}'_{\mathrm{v}}\mathbf{C})$) is the first round indirect (forward-linkage) production effects of the direct production effect in sector i. This means that the additional increase in price margin in sector i (e.g., **A** times one cent per \$1) is required by i and other sectors (as their input price). This interpretation applies to the third term ($\mathbf{A}^2(\mathbf{p}'_{\mathrm{v}}\mathbf{C})$) and others as well, and these round effects (i.e., the endogenous forward production effect) are assumed to be finished simultaneously. Thus, they will at last change the price of total outputs and the final outputs (e.g., m-th factor in sector j via the coefficient d_{mj}; $\Delta p_{ym}d_{mj}$).

D.2 Endogenous recovery for the survival coefficient

As noted in the conclusions (Section 6), the production capacity in the study is exogenous (based on past data). Therefore, this study does not predict when the disaster damage will converge. However, some readers may wonder how to consider the notion of resilience in the supply in an endogenous way.

Perhaps one of the simplest ideas is to consider the t-period sequential model, assuming that the final output (or the survival coefficient) recovers and depending on the realized final demand in the previous period. Let Δq_i^t be the quantity change and θ_i^t be the survival rate both in the period t. Also, let $\tilde{q}_i^t$ be the realized final output (final demand), which is the pre-disaster quantity (q_i) plus the spillover change in quantity ($\Delta\tilde{q}_i^t$). From Eq.36, the change ratio of the quantity at t is expressed:

$$\frac{\Delta q_i^t}{q_i} = \theta_i^t - 1 \qquad \text{(D2.1)}$$

Here, suppose that the survival coefficient recovers, depending on the realized final outputs. For example, a producer may not be able to carry out production activities without obtaining the required final outputs. Or, if too many final outputs are supplied in the market, some suppliers may adjust their production. Thus, in the endogenous way of thinking, suppose that the quantity change at period t+1 (Δq_i^{t*1}, or θ_i^{t+1}) is a function of the realized final demand ($\tilde{q}_i^t$, or $\Delta\tilde{q}_i^t$) at the previous period t.

$$\frac{\Delta q_i^{t+1}}{q_i} = \theta_i^{t+1} - 1 = f(\tilde{q}_i^t) \qquad \text{(D2.2)}$$

where $f(\cdot)$ denotes some endogenous function. Note that in this case we need to substitute only the initial value at t=0 (i.e., Δq_i^1, or θ_i^1) and do not need to substitute after t=1.

D.3 Sequential Interindustry Models (SIM) in Romanoff (1984) and Okuyama et al. (2004)

SIM was proposed by Romanoff (1984) and his collaborators mainly during the 1980s (for a short history, see Okuyama et al., 2004). SIM is a model that takes into account a shift in production timing. As the background, a basic LQM (Eq.3) assumes that an additional amount of final demand (y) would induce the corresponding production (x) instantly. For example, Eq.D1.1 above (Fig. S6) assumes that the round effect finishes simultaneously and instantly. This assumption is not usually realistic, however, because new production would require lead and delivery times, depending on the existing amount of inventory. In particular, a disaster often causes disruptions in production (the supply constraint), but the timing of the disruptions may not affect all sectors equally.

Following Romanoff (1984), LQM (Eq.1) is converted to a "t-period" static model where t means discrete intervals of equal duration (e.g., month or week):

$$\mathbf{x}_t = \mathbf{z}_t + \mathbf{y}_t \qquad \text{(D3.1)}$$

Given **A** is fixed, suppose delivery of intermediate output (z) at t is linked to the production at t+1 because of production time:

$$\mathbf{z}_t = \mathbf{A}\mathbf{x}_{t+1} \qquad \text{(D3.2)}$$

Thus, the t-period model is expressed as:

$$\mathbf{x}_t = \mathbf{A}\mathbf{x}_{t+1} + \mathbf{y}_t \tag{D3.3}$$

Eq.D.3.3 continues indefinitely (to t+∞) because $\mathbf{x}_{t+1}$ is nested in the t-period equation. By using the double-sided Z transform, Eq.D3.3 is solved as:

$$\mathbf{x}_t = \mathbf{y}_t + \mathbf{A}\mathbf{y}_{t+1} + \mathbf{A}^2\mathbf{y}_{t+2} + \mathbf{A}^3\mathbf{y}_{t+3} + \cdots = \sum_{r=0}^{\infty} \mathbf{A}^r\,\mathbf{y}_{t+r} \tag{D3.4}$$

Eq.D3.4 is called a core SIM of the original version, meaning that the current total production (at t) is expressed as “a power series of future series final demand orders” (Romanoff, 1984, p.354).

More realistic models have been proposed as modified SIM rather than the core SIM. The SIM literature usually considers two types of production modes: the anticipatory production mode and the responsive production mode. The former makes readymade standard products and prepares product inventories. It delivers the final outputs when production is complete. Meanwhile, the latter will make non-standard, unique products without preparing inventories. Hence, before the production is complete, it takes a lead time and production interval to deliver the final outputs.

For example, Okuyama et al. (2004) formulated the two production modes as follows. The anticipatory production mode is expressed as:

$$\mathbf{x}_t = \mathbf{A}\mathbf{x}_\sigma + \mathbf{u}_t + \mathbf{y}_t \tag{D3.5}$$

where **u** is (a vector of) the outputs to product inventories. Here, t is time interval of input application, and σ is time interval of production completion. Here, as an assumptions, the intermediate output (**Ax**) is priced at σ (i.e., product completion), not at t (i.e., input application). Meanwhile, the responsive production mode is represented as:

$$\mathbf{x}_t = \mathbf{A}\mathbf{x}_{\sigma-h-k} + \mathbf{y}_t \tag{D3.6}$$

where k is the ordering lead time, and h is the production interval. Note that Eq.D3.6 has no product inventories. Again, as an assumption, the intermediate output (**Ax**) is priced at $(\sigma - h - k)$ (i.e., the initial ordering time), not at t (i.e., input application). Thus, the combined anticipatory-responsive production model encompasses both properties of Eqs.D3.5–D3.6 as:

$$\mathbf{x}_t = \mathbf{A}\mathbf{x}_{\sigma-h-k} + \mathbf{u}_t + \mathbf{y}_t \tag{D3.7}$$

The above SIM is based on LQM, and hence, we consider rewriting SIM in terms of the LPM version as follows. First of all, LQM considers the backward linkage from demand to supply (i.e., from output to input). For example, the production ($\mathbf{x}$) itself is priced at t (input), whereas the intermediate outputs ($\mathbf{Ax}$) are priced when they are demanded (or ordered; output), such as t+1 in Eq.D3.3, σ in Eq.D3.6, and $(\sigma - h - k)$ in Eqs.3.6–3.7. Thus, in SIM, the current input price is decided by the future output price (Eq.D3.4). Meanwhile, LPM (this study) considers the forward linkage from supply to demand (i.e., from input to output). Therefore, contrary to the normal SIM, in LPM, the future output price should be decided by the current input prices.

Specifically, we convert the original core SIM (Eqs.D3.1–D3.4) as follows. First, LPM (Eq.4) is converted to a t-period static model (similarly to Eq.D3.1):

$$(\mathbf{p}')_t = (\mathbf{p}'_{\mathrm{z}})_t + (\mathbf{p}'_{\mathrm{v}}\mathbf{C})_t \tag{D3.8}$$

where $\mathbf{p}'_{\mathrm{z}}$ is the price vector of intermediate inputs (z), and $(\cdot)_t$ means a period t. For simplicity, suppose that $\mathbf{C}$ may be variable at t. Given that $\mathbf{A}$ is fixed, suppose that the price for intermediate inputs at t is linked to the production at t–1 because of production time:

$$(\mathbf{p}'_{\mathrm{z}})_t = (\mathbf{p}')_{t-1}\mathbf{A} \tag{D3.9}$$

Thus, the t-period model is expressed as:

$$(\mathbf{p}')_t = (\mathbf{p}')_{t-1}\mathbf{A} + (\mathbf{p}'_{\mathrm{v}}\mathbf{C})_t \tag{D3.10}$$

Eq.D.3.10 continues negatively indefinitely (to t–∞) because $(\mathbf{p}')_{t-1}$ is nested in the t-period equation. By using the double-sided Z transform, Eq.D3.10 is solved as:

$$(\mathbf{p}')_t = (\mathbf{p}'_{\mathrm{v}}\mathbf{C})_t + \mathbf{A}(\mathbf{p}'_{\mathrm{v}}\mathbf{C})_{t-1} + \mathbf{A}^2(\mathbf{p}'_{\mathrm{v}}\mathbf{C})_{t-2} + \mathbf{A}^3(\mathbf{p}'_{\mathrm{v}}\mathbf{C})_{t-3} + \cdots = \sum_{r=0}^{\infty} \mathbf{A}^r\, \mathbf{y}_{t-r} \tag{D3.11}$$

This part refers Eq.D3.11 to the original core SIM of the LPM version, meaning that the current total price (at t) is expressed as a power series of past series the price of primary inputs (to t–∞) have induced.

In addition, analogously to Eqs.D3.5–D3.7, we may consider the combined anticipatory-responsive production model for the LPM version as follows. As the simplest idea, we suppose that the correspondence between the time intervals of input (e.g., supply at t) and output (e.g., demand at σ) can be reversed from LQM, as in Okuyama et al. (2004), because LPM is the supply-driven model. For example, the anticipatory production mode may be expressed as:

$$(\mathbf{p}')_\sigma = (\mathbf{p}')_t\mathbf{A} + (\mathbf{p}'_{\mathrm{v}}\mathbf{C})_\sigma \tag{D3.12}$$

where t is time interval of input application, and σ is time interval of production completion. It is assumed that prices for total outputs $(\mathbf{p}')$ and primary inputs $(\mathbf{p}'_{\mathrm{v}}\mathbf{C})$ are priced at σ (when production is complete), and the price for intermediate inputs $(\mathbf{p}'\mathbf{A})$ is priced at t (when input is applied). Note that Eq.D3.12 ignores the inventory price, assuming that the inventory is priced at σ (at the completion of production).

Meanwhile, the responsive production mode of the LPM version may be expressed as:

$$(\mathbf{p}')_{\sigma-h-k} = (\mathbf{p}')_t\mathbf{A} + (\mathbf{p}'_{\mathrm{V}}\mathbf{C})_{\sigma-h-k} \tag{D3.13}$$

where k is the ordering lead time and h is the production interval. It is assumed that prices for total outputs $(\mathbf{p}')$ and primary inputs $(\mathbf{p}'_{\mathrm{V}}\mathbf{C})$ are priced at $(\sigma - h - k)$ because production will take place after ordering at $(\sigma - h - k)$. Note that Eq.D3.13 is also considered as the combined anticipatory-responsive production model for LPM because it already encompasses the property of Eq.3.12.

D.4 Impact on transportation networks in Sohn et al. (2004) and Kim et al. (2002)

The production network is a key issue in the literature on disasters. As a study of this challenging issue, this section would like to review Sohn et al. (2004), who examined the economic impacts of an earthquake on transportation. The authors analyzed the period from the base year (1993) to 2017 (as a forecast) in 36 earthquake analysis zones in 13 economic sectors in the United States. For background, in recent decades, supply chains have become more developed (not only domestically but also globally), probably because the costs of transfers and transportation have become much lower. In other words, transportation intensity (or transportation efficiency) in the supply chain network has increased a lot, leading to an increase in the fragmentation of production. However, the efficiency here relies on eliminating wasteful networks, which can result in a loss of resilience. Therefore, when a disaster disrupts the supply chains, the more efficient the production network, the greater the damage to production.

The model of Sohn et al. (2004) is divided into two parts. One part is the integrated commodity flow model (ICFM) (Sohn et al., 2004, Section 12.6, pp.247–249), which was proposed in Kim et al. (2002, Eqs.1–8 in Section 3, pp.226–229) and related papers. Note that ICFM is based partly on but far from the ordinary IO models, and therefore, this section does not fully review ICFM from the viewpoint of IOA. The other is the final demand loss function (Sohn et al., 2004, Section 12.5, pp.242–247), which is based on LQM.

Specifically, ICFM seeks to find the total transportation costs in the economic system, which are the network assignment costs, intraregional travel costs, and interregional flow distribution costs. This estimate is subject to the following three conditions: material balance, conservation of flow, and nonnegativity of the flow (of the output of sector). Sohn et al. (2004, Eq.12.17, p.249) calculated the change in a sectoral system-wide transportation cost (ΔTC_i) in sector i.

Meanwhile, regarding the final demand loss function (Sohn et al., 2004, Eq.12.8, p.242), we can simplify it as follows. First of all, the loss of final demand ($\Delta\mathbf{y}$) is based on LQM as:

$$\mathbf{y} = (\mathbf{I} - \mathbf{A})\mathbf{x} \Leftrightarrow \Delta\mathbf{y} = (\mathbf{I} - \mathbf{A})\Delta\mathbf{x} \tag{D4.1}$$

given that $\mathbf{A}$ is fixed. As the steps for estimation, we first estimate the transportation cost (ΔTC_i) by ICFM and the corresponding loss of production ($\Delta\mathbf{x}$). Eq.D4.1 then estimates the loss of final demand ($\Delta\mathbf{y}$) as the economic loss. Specifically, in a manner similar to the survival coefficient (θ) in the main text, $\Delta\mathbf{x}$ is caused by the network disruption (coefficient):

$$\Delta\mathbf{x} = \mathbf{N} \otimes (\mathbf{I} - \mathbf{R}) \circ \mathbf{x} \tag{D4.2}$$

$\mathbf{N}$ is the matrix of network disruption ratio (by zone) (i.e., the symbol $\mathbf{D}$ is used in Sohn et al. (2004), but we use $\mathbf{N}$ to distinguish it from the other coefficient $\mathbf{D}$ in the main text). $\mathbf{R}$ is the matrix of sectoral resiliency factor, and thus, $(\mathbf{I} - \mathbf{R})$ represents a negative factor of sectoral resiliency. $\otimes$ means the multiplier of tensor product. "$\circ$" denotes the multiplier of Hadamard product (i.e., the element-wise product). Here, the network disruption is represented as the network disruption ratio ($\mathbf{N}$) times the sectoral resiliency ratio $(\mathbf{I} - \mathbf{R})$, meaning that the greater the network disruption and the lower the resilience, the greater the damage to production. Recall that $\mathbf{x}$ is $(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, and the final demand loss function of Sohn et al. (2004) is derived as:

$$\Delta\mathbf{y} = (\mathbf{I} - \mathbf{A})\{[\mathbf{N} \otimes (\mathbf{I} - \mathbf{R})] \circ \mathbf{x}\} = (\mathbf{I} - \mathbf{A})\{[\mathbf{N} \otimes (\mathbf{I} - \mathbf{R})] \circ [(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}]\} \tag{D4.3}$$

This part reviews the model of Sohn et al. (2004). First of all, ICFM itself will be helpful for examining the network in each region when considering each material flow. It is also beneficial for calculating the transportation costs (ΔTC).

Meanwhile, regarding the final demand loss function, this part wonders if it is inconsistent with the IOA theory. The strangest point is that Eq.D4.1 (LQM) calculates the demand loss ($\Delta\mathbf{y}$) by the production loss ($\Delta\mathbf{x}$) although LQM is the demand-driven model. Instead, we rewrite the final demand loss function for the supply-driven model as follows.

The simplest idea changes Eq.D4.2 to the quantity equation, analogously to the survival coefficient (θ). For simplicity, before a disaster, we assume that production $(\mathbf{x})$ equals quantity $(\mathbf{q})$ at price $(\mathbf{p})$ is one. First, suppose that the network disruption causes the supply constraint, and Eq.D4.2 is rewritten to the quantity level:

$$\Delta\mathbf{q} = \mathbf{N}\otimes(\mathbf{I} - \mathbf{R}) \circ \mathbf{q} \tag{D4.4}$$

Thus, $\mathbf{N}\otimes(\mathbf{I} - \mathbf{R})$ is analogous to the survival coefficient (θ). Thus, we can obtain the quantity loss in a certain sector i (Δq_i) and substitute it to Eq.35.

Rather, suppose that we already know how much the additional transportation cost (ΔTC) will be after a disaster (e.g., via ICFM). Usually, however, ΔTC is value added only in the transport sector and is an intermediate input in the other sectors. Therefore, separately, the price of value added is increased by ΔTC divided by q in the transport sector as follows:

$$\Delta(p_v'c) = \frac{\Delta TC}{x} = \frac{\Delta TC}{q} \text{ in the transport sector} \tag{D4.5}$$

Meanwhile, the price of intermediate input is increased by ΔTC divided by **Ax** in other sectors as follows:

$$\Delta(p'a) = \frac{\Delta TC}{ax} \text{ in other sectors except for the transport sector} \tag{D4.6}$$

In this way, we can use the information on the additional prices of value added $(\mathbf{p}_{\mathrm{v}}'\mathbf{C})$ and the intermediate inputs $(\mathbf{p}'\mathbf{A})$ in IOA. For example, we may consider updating the coefficients **A** to $\mathbf{A}_{\mathbf{new}}$, or **C** to $\mathbf{C}_{\mathbf{new}}$.

D.5 Input-occupancy-output model in Chen (1990) and Chen et al. (2005)

Usually, LQM (the Leontief production function) assumes a fixed proportion of inputs (i.e., the fixed **A**), meaning that one product (one output) requires a fixed proportion of inputs. In other words, LQM does not consider capital assets such as the plant, land, labor, and other forms. However, this assumption may not be realistic because, without capital assets, no matter how many inputs, no output can be produced. For example, in a car supply chain, a car (output) is usually made up of tens of thousands of parts (inputs). Now, suppose that a disaster damages a plant that creates a key automobile part that cannot be replaced or substituted in order to complete a car. As a result, car production would not be complete just because the plant cannot operate.

As a model for considering such a capital (or asset) constraint, the input-occupancy-output model (or, the IO model with assets) was proposed in Chen (1990) and Chen et al. (2005). The term "occupancy" means "holding and using assets at a point of time by a sector, where assets include fixed assets, inventory, financial assets, labor, natural resources, and so on" (Chen et al., 2005, p.224). Chen et al. (2005, p.213) explained assets in terms of the following three features: "assets consist not only of fixed assets (such as machinery and construction), but also of inventories, financial assets, labor force (educated or not, skilled or not), natural resources, intangible assets, and others;" where "(1) assets are a prerequisite for input and output...; (2) assets are related with output and input...; and (3) input is dependent on the assets used."

Regarding the normal LQM, which does not consider capital assets, Chen et al. (2005, Eqs.8–9, p.218) first rewrote LQM as follows:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = (\mathbf{A_B} + \mathbf{I})\mathbf{y} \tag{D5.1}$$

$$\text{where } \mathbf{A_B} = (\mathbf{I} - \mathbf{A})^{-1} - \mathbf{I} \tag{D5.2}$$

Instead of $\mathbf{B}$ in Chen et al. (2005), we use $\mathbf{A_B}$ to distinguish it from the coefficient $\mathbf{B}$ in the main text. Notice that compared to the Leontief inverse $\mathbf{L}$, $\mathbf{A_B}$ ignores the identity matrix $\mathbf{I}$:

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots \tag{D5.3}$$

$$\mathbf{A_B} = (\mathbf{I} - \mathbf{A})^{-1} - \mathbf{I} = \mathbf{A}(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots \tag{D5.4}$$

Here, Chen et al. (2005, p.218) considered to include the indirect "consumption" of fixed assets, rewriting $\mathbf{A_B}$ to $\mathbf{A_B^*}$ as follows:

$$\mathbf{A_B^*} = \mathbf{A} + \mathbf{A_B^*}\mathbf{A} + \widehat{\alpha}\mathbf{A_D} + \mathbf{A_B^*}\widehat{\alpha}\mathbf{A_D} = (\mathbf{A} + \widehat{\alpha}\mathbf{A_D}) + \mathbf{A_B^*}(\mathbf{A} + \widehat{\alpha}\mathbf{A_D}) \tag{D5.5}$$

Note that, instead of $\mathbf{D}$ in Chen et al. (2005), we use $\mathbf{A_D}$ to distinguish it from the coefficient $\mathbf{D}$ in the main text. $\mathbf{A_D}$ is $I \times I$-matrix with the fixed asset holding coefficient. $\widehat{\alpha}$ is the diagonal matrix of the depreciation rate α_i. In the middle part of Eq.D5.5, the first term $(\mathbf{A})$ means the direct consumption coefficient via intermediate inputs; the second term denotes $(\mathbf{A_B^*}\mathbf{A})$ the indirect consumption via intermediate inputs; the third term $(\widehat{\alpha}\mathbf{A_D})$ denotes the direct consumption via fixed assets, which is the product of the depreciation rate $(\widehat{\alpha})$ and the fixed asset holding coefficient $(\mathbf{A_D})$; and the fourth term $(\mathbf{A_B^*}\widehat{\alpha}\mathbf{A_D})$ refers to the indirect consumption via fixed assets. Notice that Eq.D5.5 has round (or ripple) effects because of including $\mathbf{A_B^*}$ in the two terms in the middle part. The third part shows that $\mathbf{A_B^*}$ is divided into the direct consumption coefficients $(\mathbf{A} + \widehat{\alpha}\mathbf{A_D})$ and the indirect ones $\mathbf{A_B^*}(\mathbf{A} + \widehat{\alpha}\mathbf{A_D})$.

Note that we can rewrite Eq.D5.5 as follows:

$$\mathbf{A_B^*}\{\mathbf{I} - (\mathbf{A} + \widehat{\alpha}\mathbf{A_D})\} = \mathbf{A} + \widehat{\alpha}\mathbf{A_D} \tag{D5.6}$$

Or, equivalently, using Eq.D5.4:

$$\mathbf{A_B^*} = (\mathbf{A} + \widehat{\alpha}\mathbf{A_D})\{\mathbf{I} - (\mathbf{A} + \widehat{\alpha}\mathbf{A_D})\}^{-1} = \{\mathbf{I} - (\mathbf{A} + \widehat{\alpha}\mathbf{A_D})\}^{-1} - \mathbf{I} \tag{D5.7}$$

Chen et al. (2005, Eqs.15–16, p.220) compared the normal LQM with their approach, replacing $\mathbf{A}$ with $(\mathbf{A}+\hat{\alpha}\mathbf{A_D})$ as follows:

$$\mathbf{x}=(\mathbf{A}+\hat{\alpha}\mathbf{A_D})\mathbf{x}-\hat{\alpha}\mathbf{A_D}\mathbf{x}+\mathbf{y}=(\mathbf{A}+\hat{\alpha}\mathbf{A_D})\mathbf{x}+\mathbf{y}^* \tag{D5.8}$$

where $\mathbf{y}^*$ represents the vector of net final demands, excluding the replacement investments of fixed assets $(-\hat{\alpha}\mathbf{A_D}\mathbf{x})$. Eq.D5.8 considers the consumption via fixed assets as the intermediate outputs $(\hat{\alpha}\mathbf{A_D}\mathbf{x})$ but removes the same amount of consumption from the final demand $(-\hat{\alpha}\mathbf{A_D}\mathbf{x})$ because of equality. Thus, we can estimate that the additional net final demand ($\mathbf{y}^*$) would increase how much in terms of production as follows:

$$\mathbf{x}=\{\mathbf{I}-(\mathbf{A}+\hat{\alpha}\mathbf{A_D})\}^{-1}\mathbf{y}^* \tag{D5.9}$$

From here, as the simplest application, we explain how the model of this study (i.e., LPM) can integrate the input-occupancy-output model. First, considering the coefficient via fixed assets ($\hat{\alpha}\mathbf{A_D}$), we rewrite the Leontief inverse $\mathbf{L}$ to $\mathbf{L}^*$ as follows:

$$\mathbf{L}^*=\{\mathbf{I}-(\mathbf{A}+\hat{\alpha}\mathbf{A_D})\}^{-1} \tag{D5.10}$$

Note that $\hat{\alpha}\mathbf{A_D}$ may take large values if a disaster causes a huge amount of damage to the fixed assets. Thus, replacing $\mathbf{L}$ in Eq.45 with $\mathbf{L}^*$, we represent the price of total outputs plus the unit cost of occupying fixed assets $(\Delta\tilde{\mathbf{p}}'^*)$ as follows:

$$\Delta\tilde{\mathbf{p}}'^*=\Delta(\mathbf{p}_\mathrm{V}'\mathbf{C})\mathbf{L}^*=\Delta\mathbf{p}'\hat{\mathbf{c}}\mathbf{L}^*=\left[\frac{\Delta q_i}{q_i\varepsilon_i}\right]'\hat{\mathbf{c}}\mathbf{L}^*=\left[\frac{\theta_i-1}{\varepsilon_i}\right]'\hat{\mathbf{c}}\mathbf{L}^* \tag{D5.11}$$

In this way, we can examine how the change in price for primary inputs ($\Delta(\mathbf{p}_\mathrm{V}'\mathbf{C})$) will affect the price of total outputs with the unit cost of occupying fixed assets $(\Delta\tilde{\mathbf{p}}'^*)$.

D.6 Extension to the CGE model: the FIDELIO model in Kratena et al. (2013; 2017) and Kratena and Streicher (2017)

The model of this study is just an IOA, not CGE, but some readers may wonder how this study can be applied to CGE. Thus, this part briefly discusses it with reference to Fully Interregional Dynamic Econometric Long-term IO Model (FIDELIO) (Kratena et al., 2013; 2017; Kratena & Streicher, 2017). FIDELIO is very similar to CGE and has a demand-driven and linear "IO philosophy" (Kratena et al., 2013). Regarding the overview of FIDELIO, Fig. S8 (Kratena et al., 2013, Fig. 1.1, p.5) shows the main economic flows (i.e., monetary transactions, not real [quantity] flows), and Fig. S9 (Kratena et al., 2013, Fig. 1.2, p.10) indicates the selected prices.

Skipping the details, regarding the disaster analysis, FIDELIO can analyze both demand and supply constraints (i.e., shocks) because it includes the CGE essence but is more suitable for the demand constraint than the supply constraint because of following LQM (as the demand-driven model). At the middle of top of Fig. S8, $GD_{bp}(r; g; u)$ represents demand by user u for good g domestically produced in region r at basic prices (bp). As in LQM, $GD_{bp}(r; g; u)$ derives the supply of goods (gross outputs) by sector s in region r (denoted by Q(r; s)), under the constant proportions of market share (denoted by MKSH(r; g; s)) at the base year (t=0 as in the superscript). Kratena et al. (2013, Eqs.4.1–4.2, pp.70–71) express this relationship as follows:

$$\mathrm{MAKE}(\mathrm{r},\mathrm{g},\mathrm{s}) = \underline{\mathrm{MKSH}^{0}}(\mathrm{r},\mathrm{g},\mathrm{s}) \cdot \sum_{\mathrm{u}} \mathrm{GD}_{\mathrm{bp}}(\mathrm{r},\mathrm{g},\mathrm{u}) \tag{D6.1}$$

$$\mathrm{Q}(\mathrm{r},\mathrm{s}) = \sum_{\mathrm{g}} \mathrm{MAKE}(\mathrm{r},\mathrm{g},\mathrm{s}) \tag{D6.2}$$

where MAKE (r, g, s) denotes the total supply of good g by sector s in r (i.e., make matrix element). Notice that Eqs.D6.1–D6.2 are analogous to LQM (Eq.3) as:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{L}\mathbf{y} \tag{3}$$

where $\mathrm{GD}_{\mathrm{bp}}(\mathrm{r},\mathrm{g},\mathrm{u})$ is analogous to $\mathbf{y}$. Thus, FIDELIO can analyze the demand constraint (shock) via $\Delta\mathrm{GD}_{\mathrm{bp}}(\mathrm{r},\mathrm{g},\mathrm{u})$, in a manner similar to $\Delta\mathbf{y}$ in LQM.

Regarding the price, FIDELIO "distinguishes between prices at a very detailed level," and "all prices ultimately derive from output prices PQ(r,s), which are basic prices determined in the translog production block using the price function" (Kratena et al., 2013, p.90). This implies that regarding prices, FIDELIO is analogous to GPM (as the demand-driven price model). As in GPM, the output price in region r in sector s (denoted by $\mathrm{PQ}(\mathrm{r},\mathrm{s})$) derives the basic prices of domestic products (denoted by $\mathrm{PGD}_{\mathrm{bp}}(\mathrm{r},\mathrm{g})$) via the average weights (denoted by $\sum_{\mathrm{s}} \underline{\mathrm{MKSH}^{0}}(\mathrm{r},\mathrm{g},\mathrm{s})$) (Kratena et al., 2013, Eq.4.91, p.91):

$$\mathrm{PGD}_{\mathrm{bp}}(\mathrm{r},\mathrm{g}) = \sum_{\mathrm{s}} \underline{\mathrm{MKSH}^{0}}(\mathrm{r},\mathrm{g},\mathrm{s}) \cdot \mathrm{PQ}(\mathrm{r},\mathrm{s}) \tag{D6.3}$$

Note that $\mathrm{PGD}_{\mathrm{bp}}(\mathrm{r},\mathrm{g})$ is further divided into each of prices. Here, notice that Eq.D6.3 is analogous to GPM (Eq.18) as:

$$\mathbf{p} = (\mathbf{I} - \mathbf{B})^{-1}\mathbf{D}\mathbf{p}_{\mathbf{y}} = \mathbf{G}\mathbf{D}\mathbf{p}_{\mathbf{y}} \tag{18}$$

where $\mathrm{PQ(r, s)}$ is analogous to $\mathbf{p}_{\mathbf{y}}$ or $\mathbf{D}\mathbf{p}_{\mathbf{y}}$. Thus, FIDELIO can analyze the change in output prices, $\Delta\mathrm{PQ(r, s)}$, in a manner similar to $\Delta(\mathbf{D}\mathbf{p}_{\mathbf{y}})$ in GPM.

Although FIDELIO is too complex to rewrite the whole model, as an idea, we can consider converting FIDELIO to the supply-driven model for some key points. First of all, FIDELIO considers first that the final demand derives the supply values (as in LQM) and then that the output prices affect various prices (as in GPM). However, this way of thinking is the opposite of this study (Section 2.1). This study considers first that the price of primary inputs decides the output price (as in LPM), and then that the input value affects the output values (as in GQM).

Specifically, LPM (Eq.6) derives the output price ($\mathbf{p}'$) from the price of primary inputs ($\mathbf{p}'_{\mathrm{v}}\mathbf{C}$).

$$\mathbf{p}' = \mathbf{p}'_{\mathrm{v}}\mathbf{C}(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{p}'_{\mathrm{v}}\mathbf{C}\mathbf{L} \tag{6}$$

Thus, analogously, Eq.D6.3 in FIDELIO is rewritten in the opposite direction, where the input price ($\mathrm{PGD_{bp}(r, g)}$) determines the output price ($\mathrm{PQ(r, s)}$), via some function $f_1(\cdot)$.

$$\mathrm{PQ(r, s)} = f_1\left(\mathrm{PGD_{bp}(r, g)}\right) \tag{D6.4}$$

Although this study is based on LPM, the change of the input quantity (Δq_i) is supposed to decide the change in $\mathbf{p}'_{\mathrm{v}}\mathbf{C}$ (Eq.44):

$$\Delta(\mathbf{p}'_{\mathrm{v}}\mathbf{C}) = \Delta\mathbf{p}'\hat{\mathbf{c}} = \left[\frac{\Delta q_i}{q_i\varepsilon_i}\right]'\hat{\mathbf{c}} = \left[\frac{\theta_i - 1}{\varepsilon_i}\right]'\hat{\mathbf{c}} \tag{44}$$

Therefore, analogously, the input price in FIDELIO may be affected by the value added via some function $f_2(\cdot)$:

$$\mathrm{PGD_{bp}(r, g)} = f_2\left(\mathrm{VA(r, s)}\right) \tag{D6.5}$$

where $\mathrm{VA(r, s)}$ is the total value added at base price (bp) of sector s in region r. When linking Eq.44 to Eq.6, we derive Eq.45, meaning that the change in the value added (i.e., the supply constraint) affects the output price ($\Delta\tilde{\mathbf{p}}'$).

$$\Delta\tilde{\mathbf{p}}' = \Delta(\mathbf{p}'_{\mathrm{v}}\mathbf{C})\mathbf{L} = \Delta\mathbf{p}'\hat{\mathbf{c}}\mathbf{L} = \left[\frac{\Delta q_i}{q_i\varepsilon_i}\right]'\hat{\mathbf{c}}\mathbf{L} = \left[\frac{\theta_i - 1}{\varepsilon_i}\right]'\hat{\mathbf{c}}\mathbf{L} \tag{45}$$

Similarly, we can link Eq.D6.5 to Eq.D6.4 via the functions f_1 and f_2.

$$\mathrm{PQ(r, s)} = f_1\left(\mathrm{PGD_{bp}(r, g)}\right) = f_1\{f_2\left(\mathrm{VA(r, s)}\right)\} \tag{D6.6}$$

Eq.D6.6 indicates that the change in value added (i.e., $\Delta\mathrm{VA(r,s)}$) will affect the change in output price (i.e., $\Delta\mathrm{PQ(r,s)}$). Finally, the model of this study presupposes that the output price decides the output quantity, meaning that consumers buy less (more) if the output price is higher (lower) (Eq.46).

$$\Delta\tilde{q}_i = \varepsilon_i \Delta\tilde{p}_i x_i \tag{46}$$

Analogously, as rewriting Eq.D6.1 in FIDELIO, the demand for each user (u) at the base price (bp) (i.e., $\mathrm{GD_{bp}(r,g,u)}$) is decided by the output price ($\mathrm{PQ(r,s)}$) via some function $f_3(\cdot)$:

$$\sum_{\mathrm{u}} \mathrm{GD_{bp}(r,g,u)} = f_3\big(\mathrm{PQ(r,s)}\big) = f_3\big[f_1\{f_2\big(\mathrm{VA(r,s)}\big)\}\big] \tag{D6.7}$$

Note that each of users (u) may decide the demand quantity, depending on their utility functions. In this way, we can examine how the supply constraint (i.e., $\Delta\mathrm{VA(r,s)}$) can affect the demand as in the model of this study.

D.7 Spatial substitution and price multipliers: the FIDELIO model in Kratena and Streicher (2017)

Regarding advanced issues, this part discusses spatial substitution and price multipliers. That is, when a disaster causes a supply shock (i.e., supply constraint), we may wonder which areas will be damaged (i.e., spatial substitution) and how much the economic impact will be (i.e., price multipliers). As background, Kratena and Streicher (2017) recently examined the fiscal policy simulations in the aftermath of the financial crisis (i.e., the stability and magnitude of fiscal policy multipliers) using the FIDELIO model (see Supplementary Information D.6). Covering 67 countries (i.e., EU countries and rest of Europe), the simulation supposes that there is a 1% shock to GDP in Spain (as an EU economy) over a ten-year period (i.e., shocks to public expenditures, capital taxes, and transfer payments). The estimated result shows multipliers are about 1.9 (1.6) for public consumption and 1.2 (0.9) for household taxes or transfers in the case of high (low) liquidity constraints.

Regarding the spatial substitution, Kratena and Streicher (2017) simulate the effect of the shock (1% of GDP) in Spain on all 67 countries. Such an analysis is possible in the model of this study because this study is already an MRIO model (i.e., 47 prefectures in Japan).

Note, however, that FIDELIO takes various prices, whereas this study conducts a domestic model (i.e., Japan). Thus, we here consider taking various prices as in FIDEIO and as in Fig. S4 (Supplementary Information C). Suppose that the price of final output ($\mathbf{p_y}$) consists of the following four prices: prices for the final outputs of the household ($\mathbf{p_{hou}}$), government ($\mathbf{p_{gov}}$), investments (capital formation; $\mathbf{p_{inv}}$), and net exports ($\mathbf{p_{exp}}$). These prices are expressed in GPM, given the coefficient **B** is fixed.

$$\mathbf{p} = \mathbf{Bp} + \mathbf{Dp_y} = \mathbf{Bp} + \mathbf{D}[\mathbf{p_{hou}}, \mathbf{p_{gov}}, \mathbf{p_{inv}}, \mathbf{p_{exp}}] \Leftrightarrow \mathbf{D}[\mathbf{p_{hou}}, \mathbf{p_{gov}}, \mathbf{p_{inv}}, \mathbf{p_{exp}}] = (\mathbf{I} - \mathbf{B})\mathbf{p} \qquad \text{(D7.1)}$$

where the bracket means the vector (i.e., the four factors of prices). In this case, suppose that the model of this study calculates the spillover change in price ($\Delta\tilde{\mathbf{p}}$) in Eq.38. Thus, substituting $\Delta\tilde{\mathbf{p}}$ to Eq.D7.1, the change of the final output price ($\Delta(\mathbf{Dp_y})$) is calculated:

$$\Delta(\mathbf{Dp_y}) = \Delta(\mathbf{D}[\Delta\mathbf{p_{hou}}, \Delta\mathbf{p_{gov}}, \Delta\mathbf{p_{inv}}, \Delta\mathbf{p_{exp}}]) = (\mathbf{I} - \mathbf{B})\Delta\tilde{\mathbf{p}} \qquad \text{(D7.2)}$$

Therefore, some rationing scheme can divide $\Delta\mathbf{p_y}$ into each of $\Delta[\mathbf{p_{hou}}, \mathbf{p_{gov}}, \mathbf{p_{inv}}, \mathbf{p_{exp}}]$.

We then can explain the price multiplier in IOA. In LQM and LPM, the Leontief inverse (**L**) causes the round effect (see Eq.D1.1 above). Thus, the Leontief multiplier in each sector i (lm_i as the row vector) is expressed as the column sum of **L** as follows:

$$[lm_i] = \mathbf{i'L} = \mathbf{i'}(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{i'}(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots) \qquad \text{(D7.3)}$$

where **i** denotes a summation vector (of one). Similarly, the Ghosh multiplier in each sector i (gm_i as the column vector) is expressed as the column sum of **G** as follows:

$$[gm_i] = \mathbf{Gi} = (\mathbf{I} - \mathbf{B})^{-1}\mathbf{i} = (\mathbf{I} + \mathbf{B} + \mathbf{B}^2 + \mathbf{B}^3 + \cdots)\mathbf{i} \qquad \text{(D7.4)}$$

As a price multiplier, FIDELIO (the demand-driven model) should use the Ghosh multiplier (because of GPM; Eq.D7.4). Meanwhile, the model of this study (the supply-driven model) should use the Leontief multiplier (because of LPM; Eq.D7.3).

D.8 The supply constraint in GQM

Some readers also may wonder if the data of this study can be applied to the disaster models developed in previous studies. Because most of the models in the literature have adopted LQM (as the demand-driven model), however, we could not find such models that could be compared directly with this study (i.e., the supply-driven model) at the present moment. Therefore, here we compare the damage of the supply constraint in GQM as follows. Note that GQM itself is considered implausible in the IOA literature (see Section 2.3).

GQM (Eq.10) is expressed as:

$$\mathbf{x'} = \mathbf{v'}(\mathbf{I} - \mathbf{B})^{-1} = \mathbf{v'G} \Leftrightarrow \mathbf{v'} = \mathbf{x'}(\mathbf{I} - \mathbf{B}) = \mathbf{x'G}^{-1} \qquad \text{(D8.1)}$$

Given that $\mathbf{B}$ is fixed, suppose that a disaster causes the supply constraint to the primary inputs. For example, the survival coefficient (or production capacity) $\boldsymbol{\Theta} = [\theta_i]$ constrains the primary inputs directly as $\mathbf{v}'\widehat{\boldsymbol{\Theta}}$ (where $\widehat{\boldsymbol{\Theta}}$ is the diagonal matrix of $\boldsymbol{\Theta}$). Replacing $\mathbf{v}'$ with $\mathbf{v}'\boldsymbol{\Theta}$ in Eq.D8.1:

$$\mathbf{v}'\widehat{\boldsymbol{\Theta}}(\mathbf{I}-\mathbf{B})^{-1} = \mathbf{x}'(\mathbf{I}-\mathbf{B})\widehat{\boldsymbol{\Theta}}(\mathbf{I}-\mathbf{B})^{-1} = \mathbf{x}'\mathbf{G}^{-1}\widehat{\boldsymbol{\Theta}}\mathbf{G} \tag{D8.2}$$

Thus, if the primary inputs will be restricted to $\mathbf{v}'\widehat{\boldsymbol{\Theta}}$, the production ($\mathbf{x}'$) is changed (i.e., most likely decreased) to be $\mathbf{x}'\mathbf{G}^{-1}\widehat{\boldsymbol{\Theta}}\mathbf{G}$. Notice that $\mathbf{x}'\mathbf{G}^{-1}\widehat{\boldsymbol{\Theta}}\mathbf{G}$ is different from $\mathbf{x}'\widehat{\boldsymbol{\Theta}}$ although they may take similar values with each other:

$$\mathbf{x}'\mathbf{G}^{-1}\widehat{\boldsymbol{\Theta}}\mathbf{G} \neq \mathbf{x}'\widehat{\boldsymbol{\Theta}} \tag{D8.3}$$

Eq.D8.3 means that in GQM, the supply constraint is likely to decrease the production directly via $\mathbf{G}^{-1}\widehat{\boldsymbol{\Theta}}\mathbf{G}$. Compared to GQM, the model of this study does not always decrease (or even increases) the production (Section 3.4). As we can confirm, the loss of PS (ΔPS; which is the difference of half-production before and after the disaster) takes even negative values (Tables V and VI).

Supplementary Information E: IIP and disaster damage

IIP covers production (in all prefectures), shipments, and inventories, and this study uses the production IIP because it has abundant production data as an actual index. Because of the real index, however, IIP has a drawback in that it is affected not only by the direct effect of disaster but also by the indirect effect among sectors, which may be somewhat mitigated by the inventories.

The direct damage lowers IIP due to labor and capital damage. The indirect damage may further lower IIP due to the balance (i.e., bottleneck) of supply and demand in the supply chain. Note, however, that this indirect damage can be alleviated to some extent by the amount of inventory, covering shipping capacity. If there are enough amounts of inventories, because shipping capacity can be covered by inventory to some extent, production damage does not spill over to the whole supply chain.

For example, suppose there are five sectors in a product supply chain: raw materials, components, and manufacture as the manufacturing sector, retail as the service sector, and the final consumers (Supplementary Information Fig. S2). The first (raw material) to fourth (retail) sectors are on the supply side, and are involved in conducting production, shipments, and inventory processes (which are all covered by IIP). The maximum volume of shipments depends on production and inventory, and shipments are realized based on the balance between supply and demand. Meanwhile, the second to last (consumer) sectors are on the demand side, purchasing a product from each of the preceding suppliers.

Suppose a disaster stops only the production of raw material. The decrease in production will affect shipping capacity, potentially changing demand (e.g., volume and price) as the intermediate input of components. Because of the shortage of the intermediate input, the supply of components may be affected, potentially changing demand for the components in the manufacturing sector (etc.). Note, however, that inventory is important for such indirect damage. If there is no inventory, production damage directly affects shipping capacity, and therefore largely affects supply and demand throughout the supply chain. Meanwhile, if there are enough inventories, because shipping capacity can be covered by inventory to some extent, production damage does not spill over to the entire supply chain.

Supplementary Information F: Indirect damages in H95Jan (Toyoda & Kouchi, 1997) and GEJE (Hayashi, 2012)

In disaster studies, the loss of SS is not widespread for estimating damage. Instead, two popular damages are direct damage (e.g., damage to capital stock) and indirect damage (e.g., flow damage due to the spillover effect). This study supposes that the loss of SS is similar to indirect damage because it does not consider the damage to capital stock and so on. In other words, the indirect damage in the previous studies is divided into those of buyers (in the downstream sector) and sellers (in the upstream sector), which are similar to the losses of CS and PS, respectively. This study supposes that the reason SS is not popular is that CS is difficult to estimate (although PS is easy). CS is calculated from the difference between reservation price (i.e., willingness-to-pay price) and transaction price. However, the reservation price is usually difficult to estimate. Meanwhile, PS is calculated from the difference between the transaction price and cost, which are easy to determine (with assumptions).

Two previous studies that estimated damage due to H95Jan (Toyoda & Kouchi, 1997) and GEJE (Hayashi, 2012) are introduced for comparative purposes (see Supplementary Information Table S10). Shortly after H95Jan (April 5, 1995), the Hyogo prefectural government (and National Land Agency, Japan) estimated that the direct damage (to capital stock) caused by the disaster totaled 9,926.8B JPY. Toyoda and Kouchi (1997) aimed to update this estimate using a questionnaire survey, which asked sample firms about direct and indirect damage amounts. The survey period spanned January 29 to February 15, 1996, and valid responses were elicited from 1,246 representatives of firms under the auspices of the Kobe Chamber of Commerce and Industry (1,086 firms for direct damage and 810 firms for indirect damage). Toyoda and Kouchi (1997) calculated disaster coefficients from the survey data and estimated the damage in ten cities and ten towns in Hyogo (which were severely damaged). The results suggest that direct damage totaled 5,930B JPY and 1,510B JPY for the industrial sectors, whereas indirect damage for one year was 7,230B JPY in total and 1,203B JPY for the industrial sectors. Based on their results, Toyoda and Kouchi (1997) argued that total direct damage should be 13,268.2B JPY.

Meanwhile, Hayashi (2012) estimated the direct and indirect damage caused by GEJE. Immediately after GEJE, the national government estimated the direct damage to be approximately 16,900B JPY (or 3.5% of GDP). Hayashi (2012) considered the additional cost of the damage and argued that the direct damage (excluding the indirect damage caused by the nuclear accident) should be valued higher, at approximately 30T JPY (6% of GDP). Also, the indirect damage was estimated to be approximately 10T JPY in Fukushima alone and approximately 100T JPY with respect to annual gross regional product over the decade. Hayashi (2012) argued that, overall, the damage caused by GEJE was three to four times higher than that caused by H95Jan.

Figs.

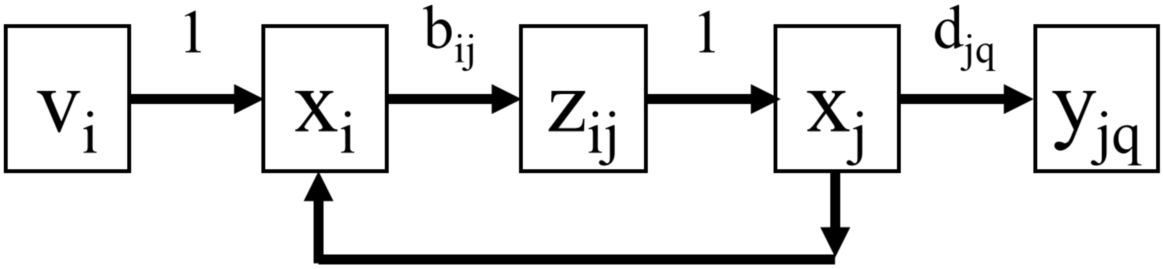

Fig. S1. Causal chain representation of the Ghoshian model (Oosterhaven, 1988, p.206, Fig. 1)

Notes: Source: Oosterhaven (1988). The original "d_{iq}" was probably a typo (i.e., "i"), and therefore, this study changes it to "d_{jq}".

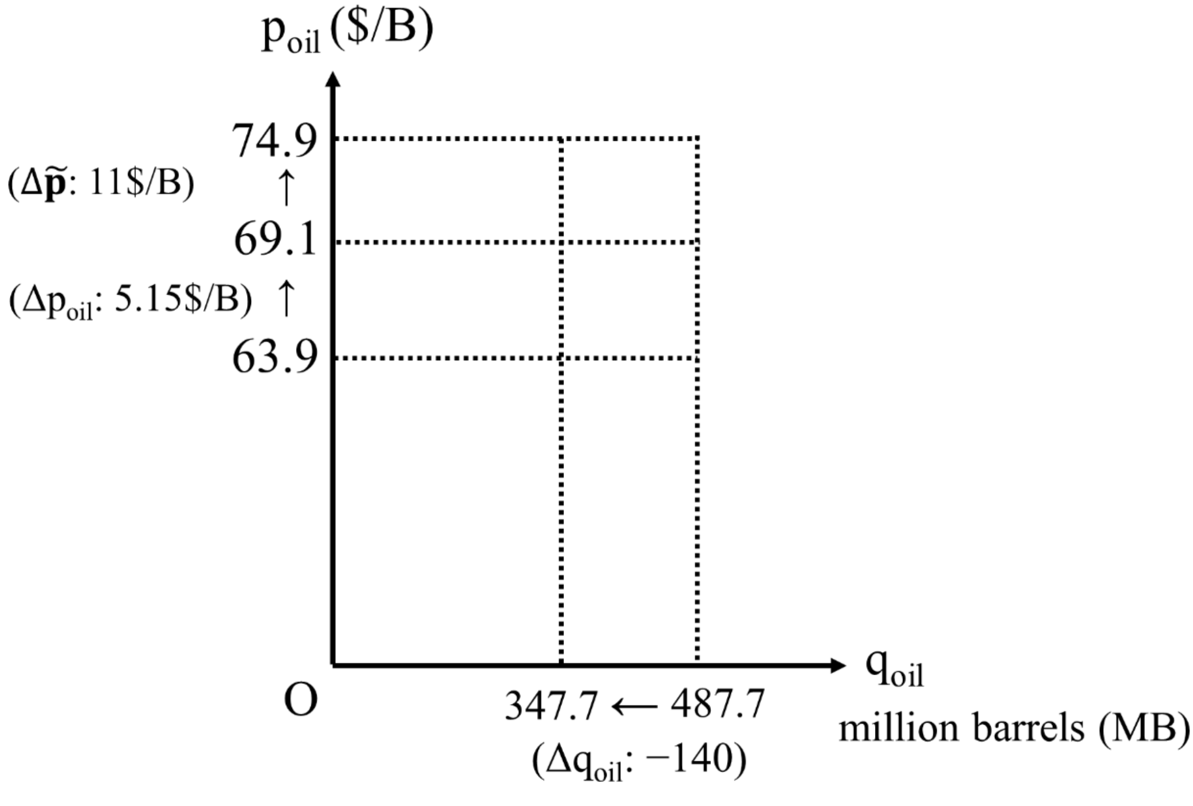

Fig. S2. Economic loss estimation in Park (2009)

Notes: The quantity (q_{oil}) was originally expected to be 487.7MB, and the quantity change (Δq_{oil}) was −140MB for the four months. The oil price before the hurricanes would be 63.9$/B. Park (2009) calculated that the direct loss (Δp_{oil}) was 5.1534 $/B (to be 69.1$/B) and that the total economic loss ($\Delta\tilde{\mathbf{p}}$) is 10.9780 $/B (to be 74.9$/B).

		Intermediate demand (**Z**: I-by-I matrix) I sectors: 1, ..., I					Final demand (**Y**: I-by-M matrix) (**y**=**Yi**: I-vector) M categories: 1, ..., M					Production (**x**: I-vector)
		1	⋯	j	⋯	I	1	⋯	m	⋯	M	
Intermediate input (**Z**: I-by-I matrix) I sectors: 1, ..., I	1	z_{11}	⋯	z_{1j}	⋯	z_{1I}	y_{11}	⋯	y_{1m}	⋯	y_{1M}	x_1
	⋮	⋮	⋱		⋰	⋮	⋮	⋱		⋰	⋮	⋮
	i	z_{i1}		z_{ij}		z_{iI}	y_{i1}		y_{im}		y_{iM}	x_i
	⋮	⋮	⋰		⋱	⋮	⋮	⋰		⋱	⋮	⋮
	I	z_{I1}	⋯	z_{Ij}	⋯	z_{II}	y_{I1}	⋯	y_{Im}	⋯	y_{IM}	x_I
Primary input (value added) (**V**: N-by-I matrix) (**v'**=**i'V**: I-vector) N categories: 1, ..., N	1	v_{11}	⋯	v_{1j}	⋯	v_{1I}						
	⋮	⋮	⋱		⋰	⋮						
	n	v_{n1}		v_{nj}		v_{nI}						
	⋮	⋮	⋰		⋱	⋮						
	N	v_{N1}	⋯	v_{Nj}	⋯	v_{NI}						
Production (**x**: I-vector)		x_1	⋯	x_j	⋯	x_I						

Fig. S3. IO table in this study

Note: To facilitate understanding by comparison, the IO model of this study follows the explanation in Oosterhaven (1996).

		Intermediate demand (**Z**: I-by-I matrix) I sectors: 1, ..., I			Final demand (**Y**: I-by-4 matrix) Four categories				Production (**x**: I-vector)
		1	⋯	I	Household (1)	Government (2)	Investment (capital formation) (3)	Net export (4)	
Intermediate input (**Z**: I-by-I matrix) I sectors: 1, ..., I	1	z_{11}	⋯	z_{1I}	y_{11} (=hou_1)	y_{12} (=gov_1)	y_{13} (=inv_1)	y_{14} (=exp_1)	x_1
	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋮
	I	z_{I1}	⋯	z_{II}	y_{I1} (=hou_i)	y_{I2} (=gov_i)	y_{I3} (=inv_i)	y_{I4} (=exp_i)	x_I
Primary input (value added) (**V**: 4-by-I matrix) Four categories	Labor (1)	v_{11} (=lab_1)	⋯	v_{1I} (=lab_I)					**lab** =$\sum lab_j$
	Capital (2)	v_{21} (=cap_1)	⋯	v_{2I} (=cap_I)		**0**			**cap** =$\sum cap_j$
	Investment (depreciation) (3)	v_{31} (=dep_1)	⋯	v_{3I} (=dep_I)					**dep** =$\sum dep_j$
	Tax (4)	v_{41} (=tax_1)	⋯	v_{4I} (=tax_I)					**tax** =$\sum tax_j$
Production (**x**: I-vector)		x_1	⋯	x_I	**hou** =$\sum hou_i$	**gov** =$\sum gov_i$	**inv** =$\sum inv_i$	**exp** =$\sum exp_i$	

Fig. S4. Example of an IO table

Notes: This figure is an example of an IO table. Regarding the demand, intermediate demand has I sectors, and final demand has four categories (household, government, investment [as capital formation], and net export [as an external sector]). Regarding the input, intermediate input has I sectors, and primary input (value added) has four categories (labor, capital, investment [as capital depreciation], and tax). Regarding the balance of supply and demand, intermediate inputs and demand are balanced (I-by-I square matrix). Meanwhile, primary input and final demand are not balanced (hence, total values do not match).

		Activity (I sectors)			Factor		Household and institutions			External	Total
		1	⋯	I	Labor	Capital	Household	Government	Investment (capital formation)	Net export	
Activity (I sectors)	1	z_{11}	⋯	z_{1j}	0	0	y_{11} (=hou_1)	y_{12} (=gov_1)	y_{13} (=inv_1)	y_{14} (=exp_1)	x_1
	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	I	z_{i1}	⋯	z_{ij}	0	0	y_{i1} (=hou_i)	y_{i2} (=gov_i)	y_{i3} (=inv_i)	y_{i4} (=exp_i)	x_i
Factor	Labor (lab)	v_{11} (=lab_1)	⋯	v_{1j} (=lab_j)	0	0	0	0	0	exp_{lab}	**lab**
	Capital (cap)	v_{21} (=cap_1)	⋯	v_{2j} (=cap_j)	0	0	0	0	0	exp_{cap}	**cap**
Household and institutions	Household	0	⋯	0	lab_{hou}	cap_{hou}	0	gov_{hou}	0	exp_{hou}	**hou**
	Government (= Tax)	v_{41} (=tax_1)	⋯	v_{4j} (=tax_1)	0	0	tax_{hou}	0	0	exp_{gov}	**gov (=tax)**
	Investment (depreciation)	v_{31} (=dep_1)	⋯	v_{3j} (=dep_j)	0	0	dep_{hou}	dep_{gov}	0	exp_{dep}	**inv (=dep)**
External	Foreign countries (= Net export)	0	⋯	0	lab_{exp}	cap_{exp}	hou_{exp}	gov_{exp}	inv_{exp}	0	**exp**
Total		x_1	⋯	$x_{j\,(=i)}$	**lab**	**cap**	**hou**	**gov (=tax)**	**inv (=dep)**	**exp**	

Fig. S5. Example of SAM

Notes: This figure is an example of SAM extended from Fig. S4. The demand (column) consists of activities (intermediate demand: I sectors), factor (labor and capital), household, government, investment (capital formation), and net export. Similarly, input (row) consists of activities (intermediate inputs: I sectors), factor (labor and capital), household, government (as tax revenue), investment (as capital depreciation), and foreign countries (as an external factor). In SAM, supply and demand are fully balanced not only in the activity sectors but also in the other sectors (hence, a square matrix).

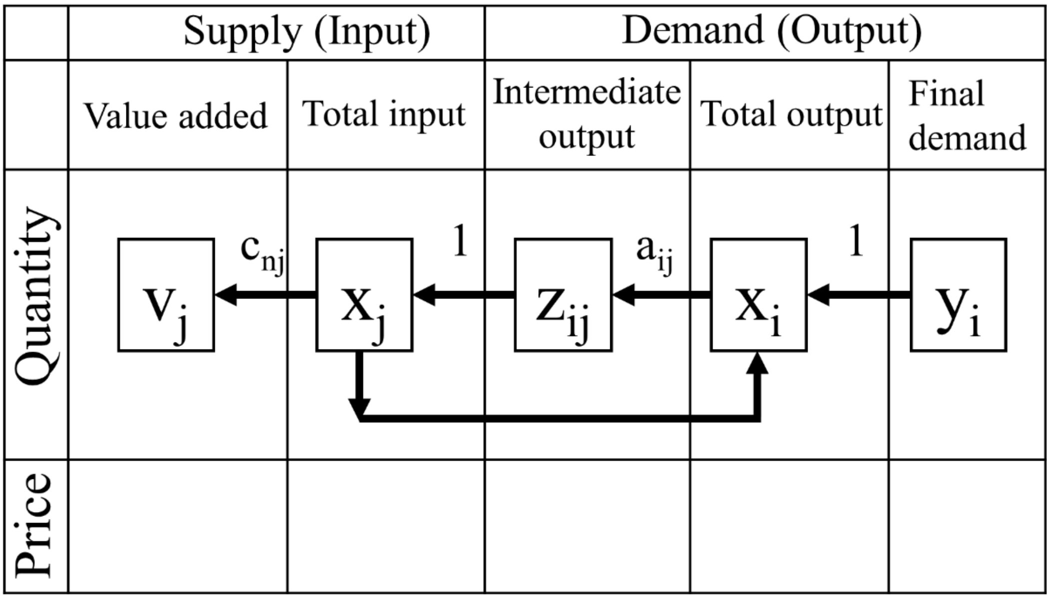

Fig. S6. The round effect of LQM

Notes: See Eq.D1.1. The change in final demand (y) causes the round effect, which affects the amount of the total input (x) and the value added (v).

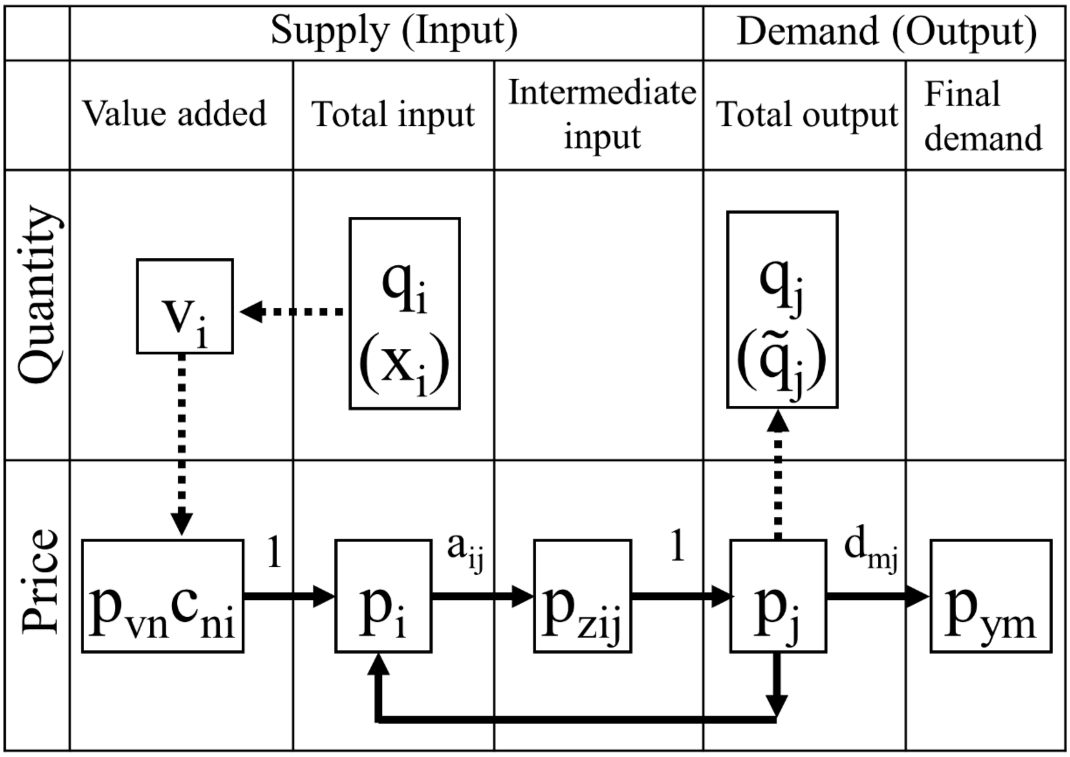

Fig. S7. The round effect of this study based on LPM

Notes: See Eq.D1.2. The quantity change (q or x) is converted to the price change for value added (p_v times c) (i.e., the dotted arrows), which causes the round effect on the prices for total outputs (p) and final demand (p_y times d) (i.e., the straight arrows). Finally, the output price (p) decides the total output quantity (q) (i.e., a dotted arrow).

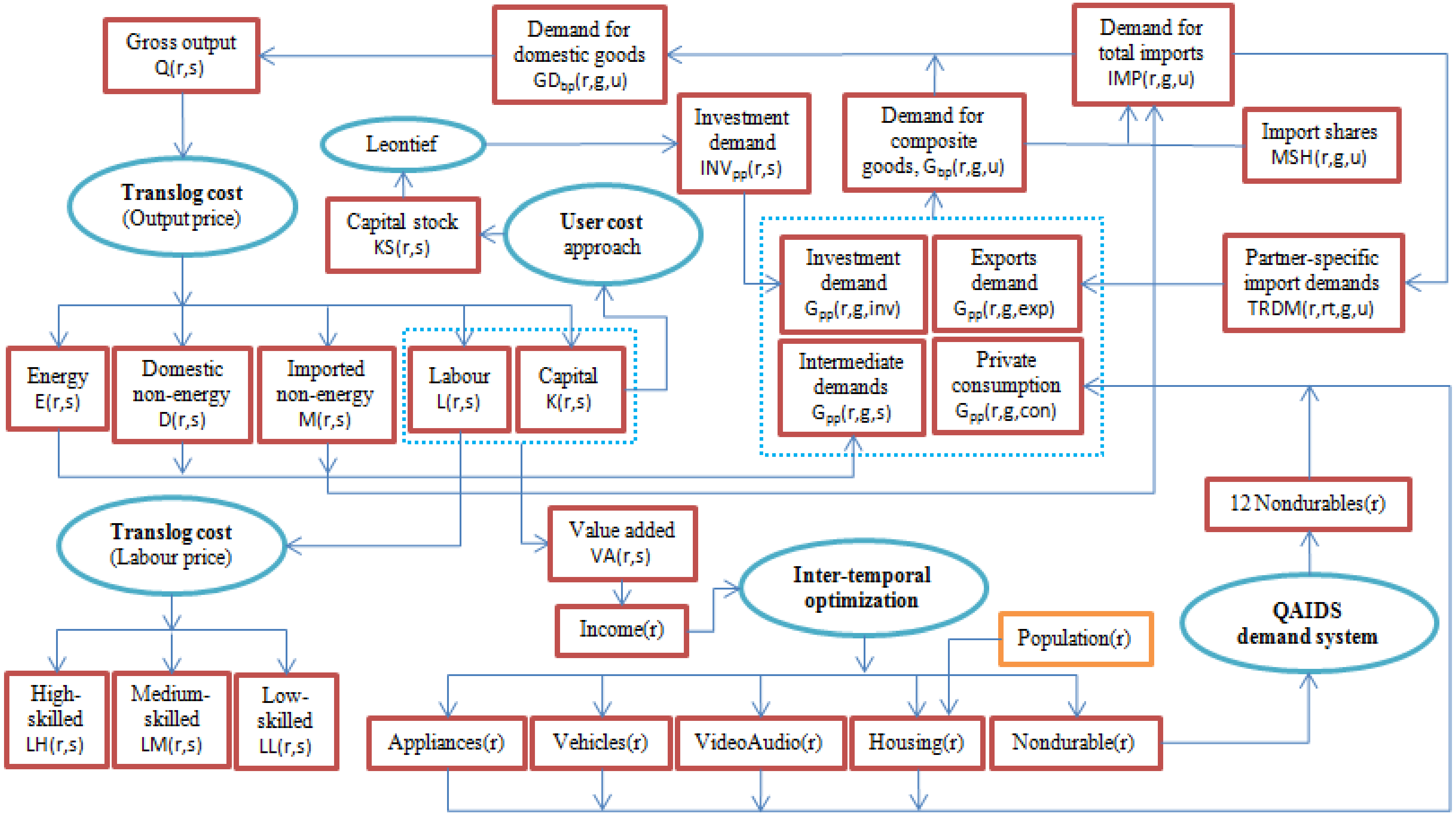

Fig. S8. Overview of the main economic flows in FIDELIO (Kratena et al., 2013, Fig. 1.1, p.5)

Notes: Source: Kratena et al. (2013, Fig. 1.1, p.5). "The variables included within red rectangles are endogenous variables. The main functional forms and approaches used for the derivation of various parts of the model are mentioned within the blue oval shapes."

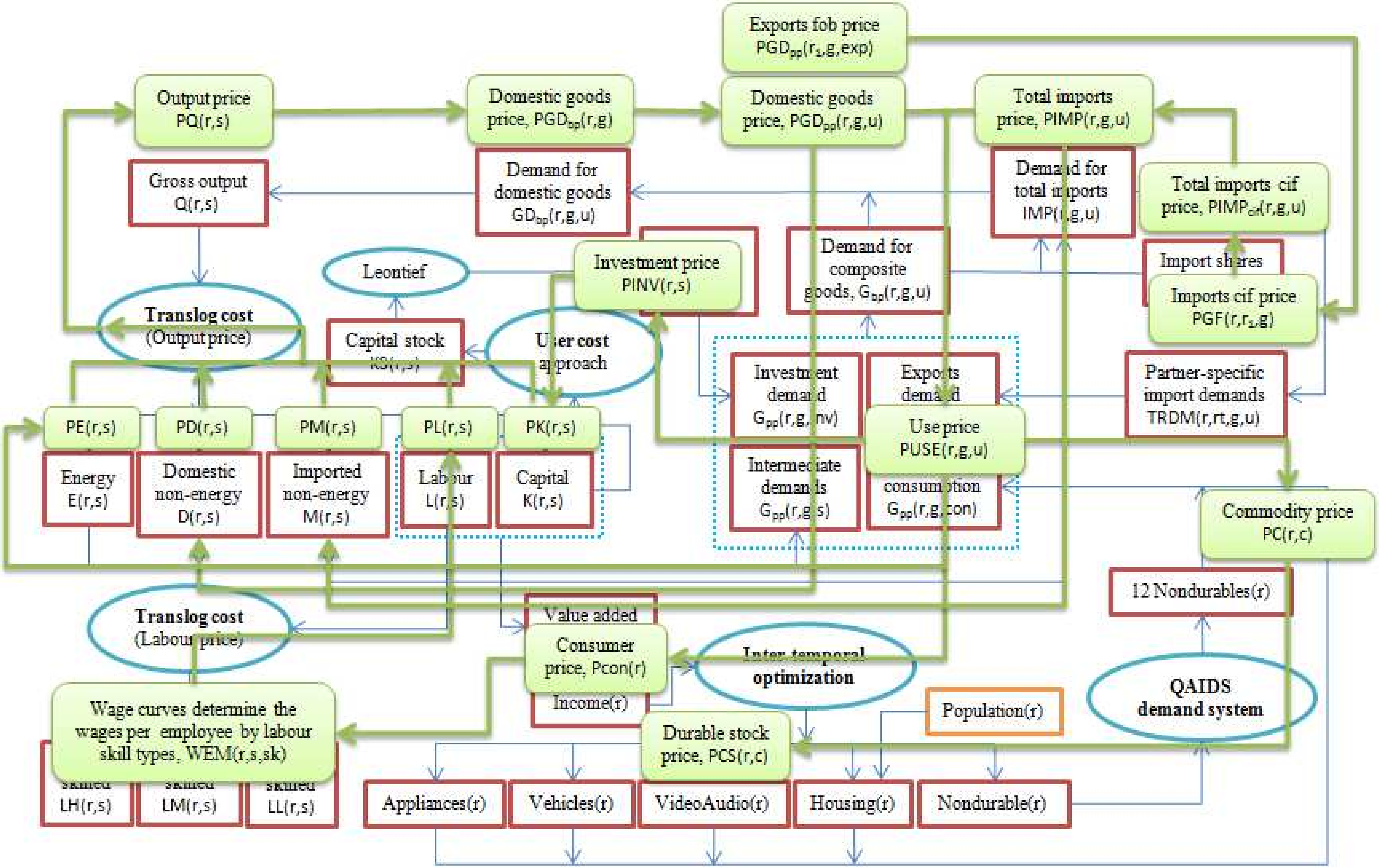

Fig. S9. Overview of selected prices in FIDELIO (Kratena et al., 2013, Fig. 1.2, p.10)

Notes: Source: Kratena et al. (2013, Fig. 1.2, p.10). “Wherever possible, prices (defined within the green rectangles) are positioned/juxtaposed with the transactions which they refer to.”

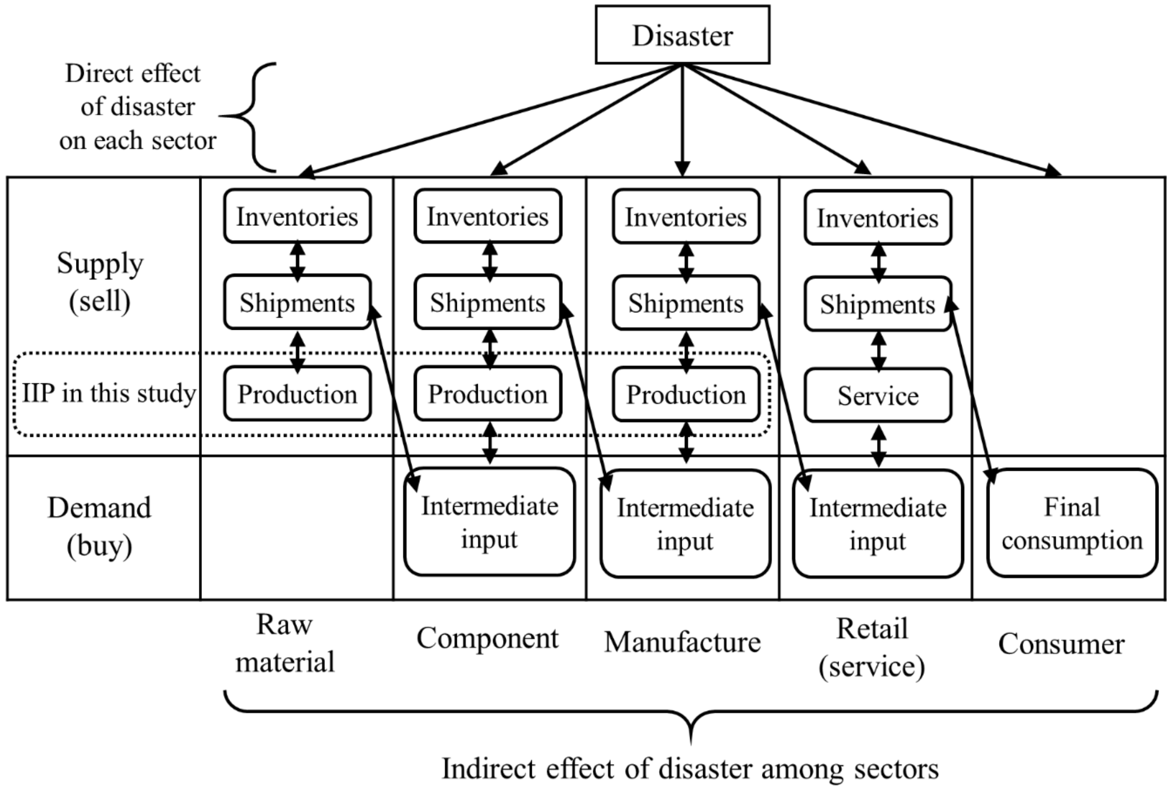

Fig. S10. Direct damage of a disaster and indirect damage among sectors in a supply chain of five sectors (as an example)

Notes: This figure shows the direct damage caused by a disaster and indirect damage among sectors in an example of a supply chain of five sectors: raw materials, components, and manufacture as the manufacturing sectors, retail as the service sector, and final consumers. The supply consists of production (or service), shipments (to the next sectors), and inventories, and demand means purchasing from the previous sectors. IIP consists of production, shipments, and inventories, and this study uses the production IIP. Shipping capacity affects demand (market price and quantity) and depends on production and inventories. If there is no inventory, production damage directly affects shipping capacity. Meanwhile, if there are enough inventories, production damage will be mitigated to some extent by covering shipping capacity.

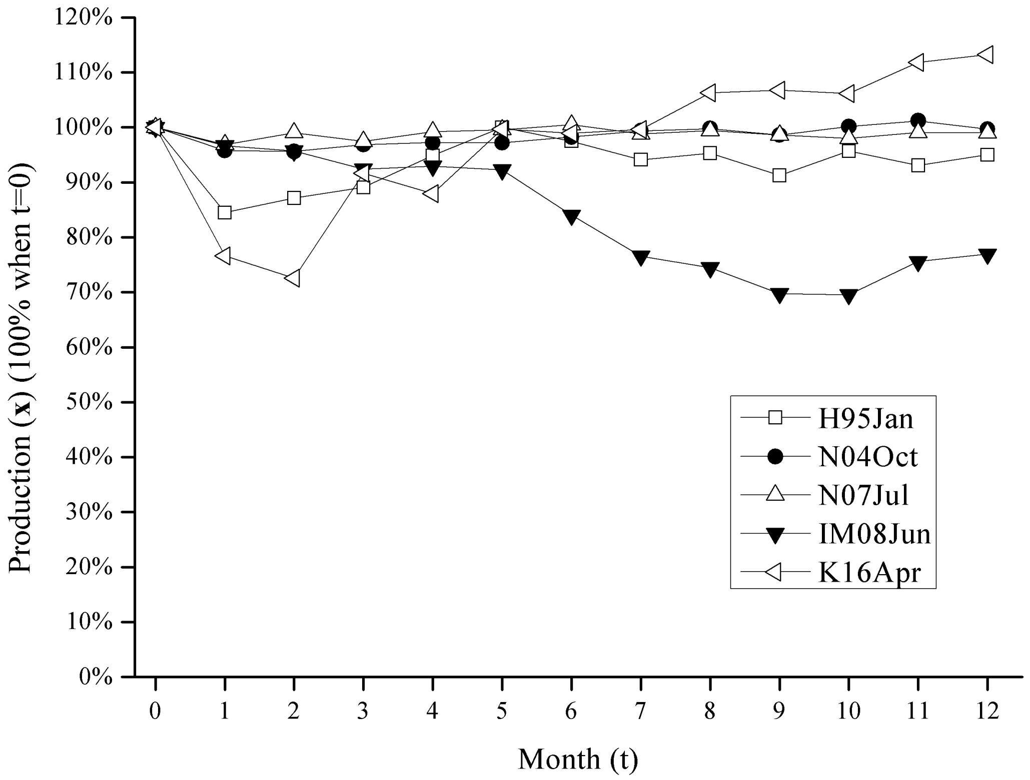

Fig. S11. Production capacity of H95Jan, N04Oct, N07Jul, IM08Jun, and K16Apr
Note: See Table III.

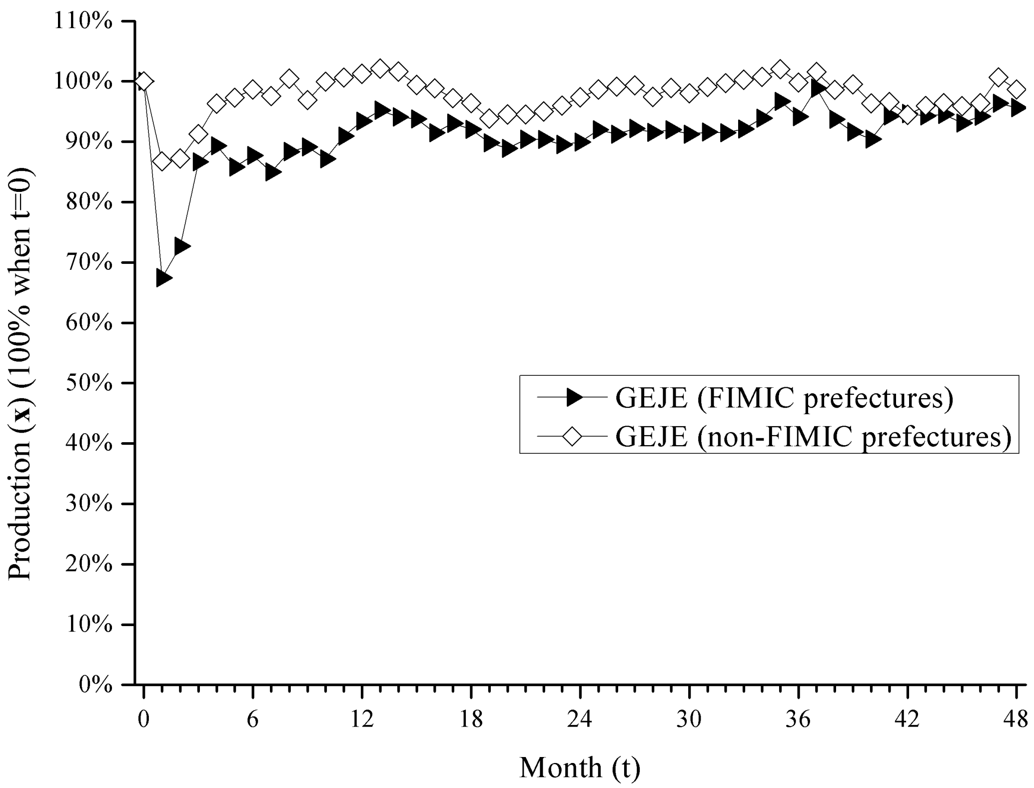

Fig. S12. Production capacity of GEJE
Note: See Table III.

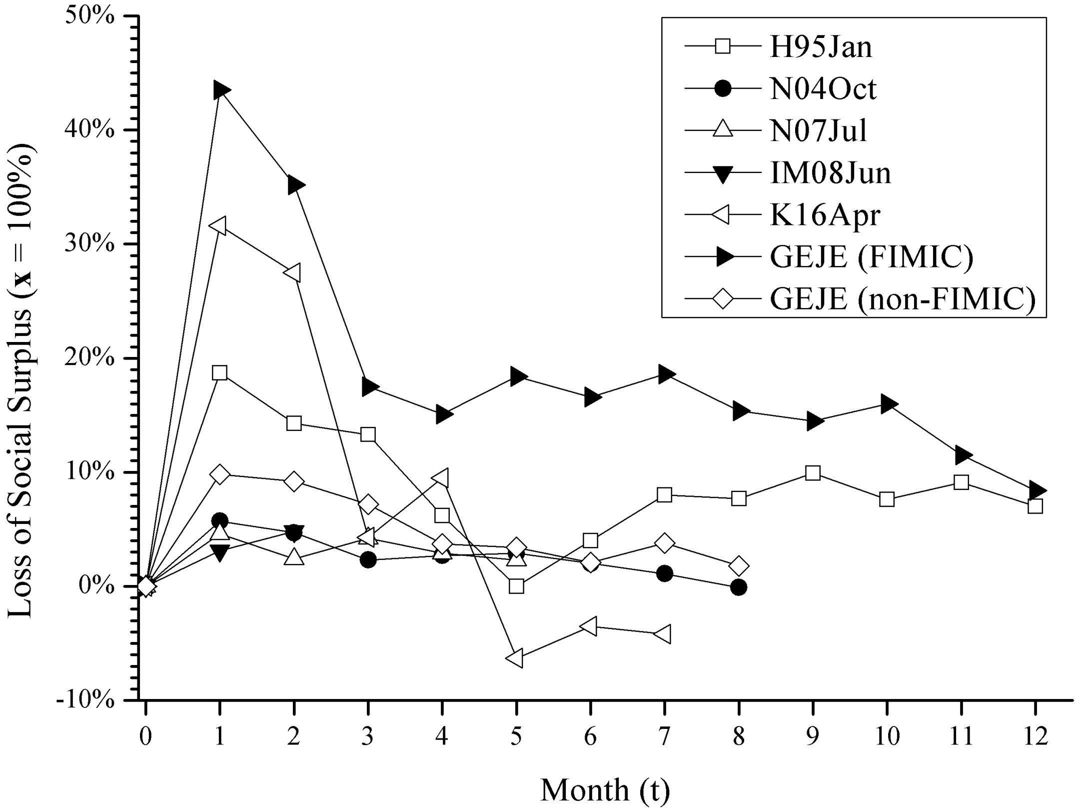

Fig. S13. Loss of social surplus (initial production is 100%)
Note: See Table V.

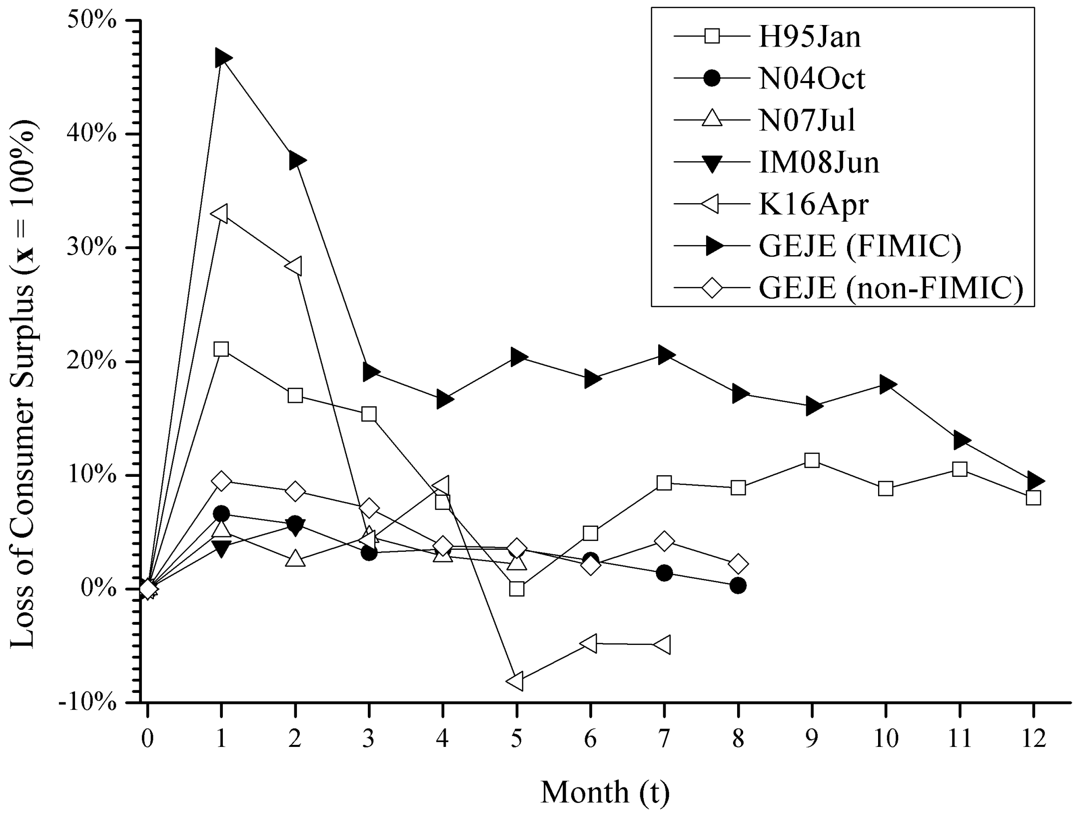

Fig. S14. Loss of consumer surplus (initial production is 100%)
Note: See Table V.

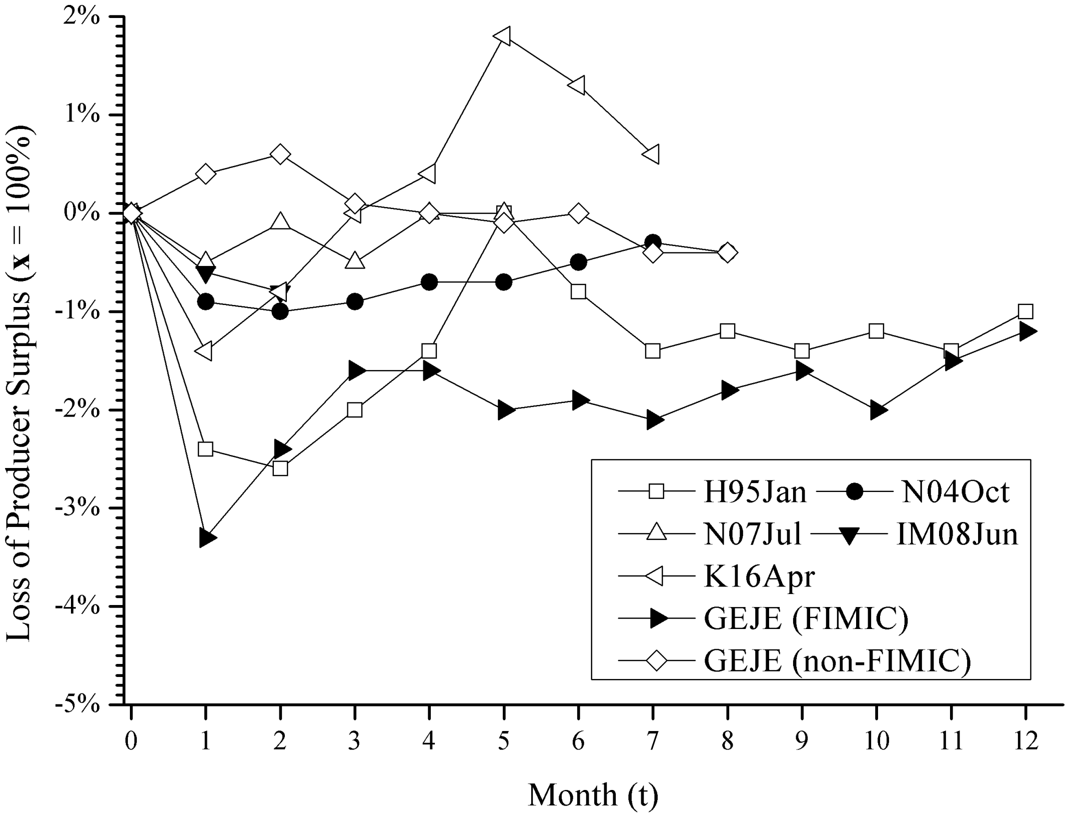

Fig. S15. Loss of producer surplus (initial production is 100%)

Note: See Table V.

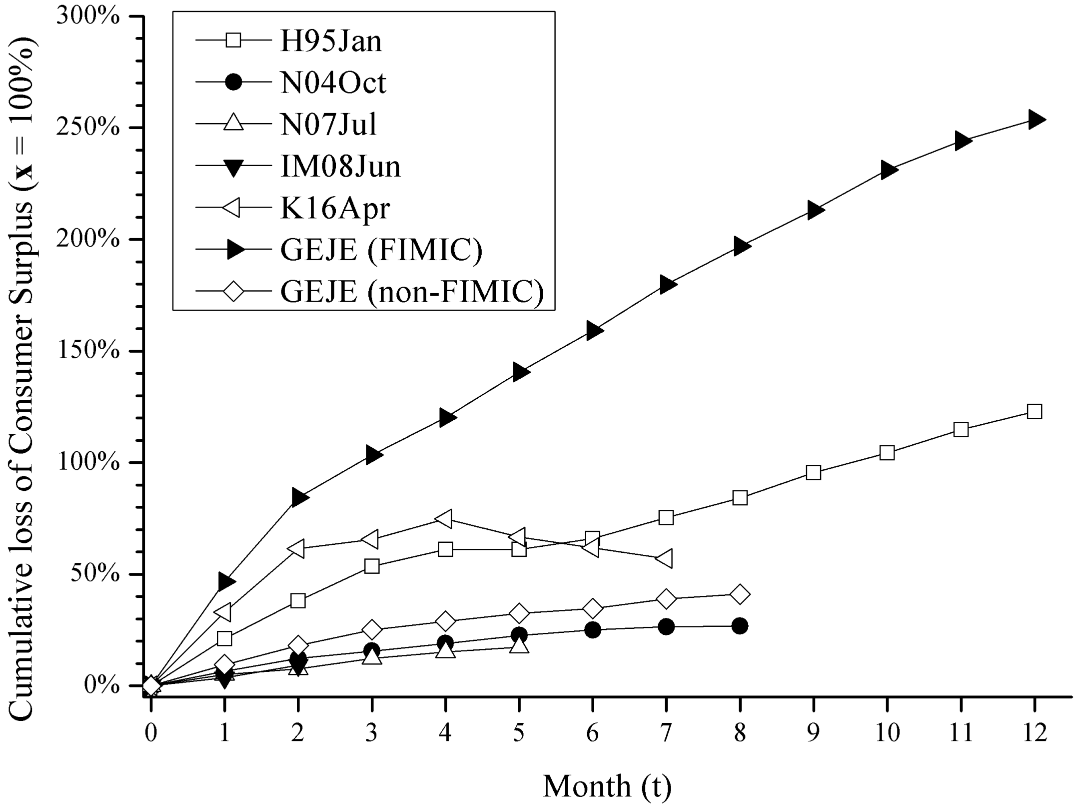

Fig. S16. Cumulative loss of consumer surplus (initial production is 100%)
Note: See Table V.

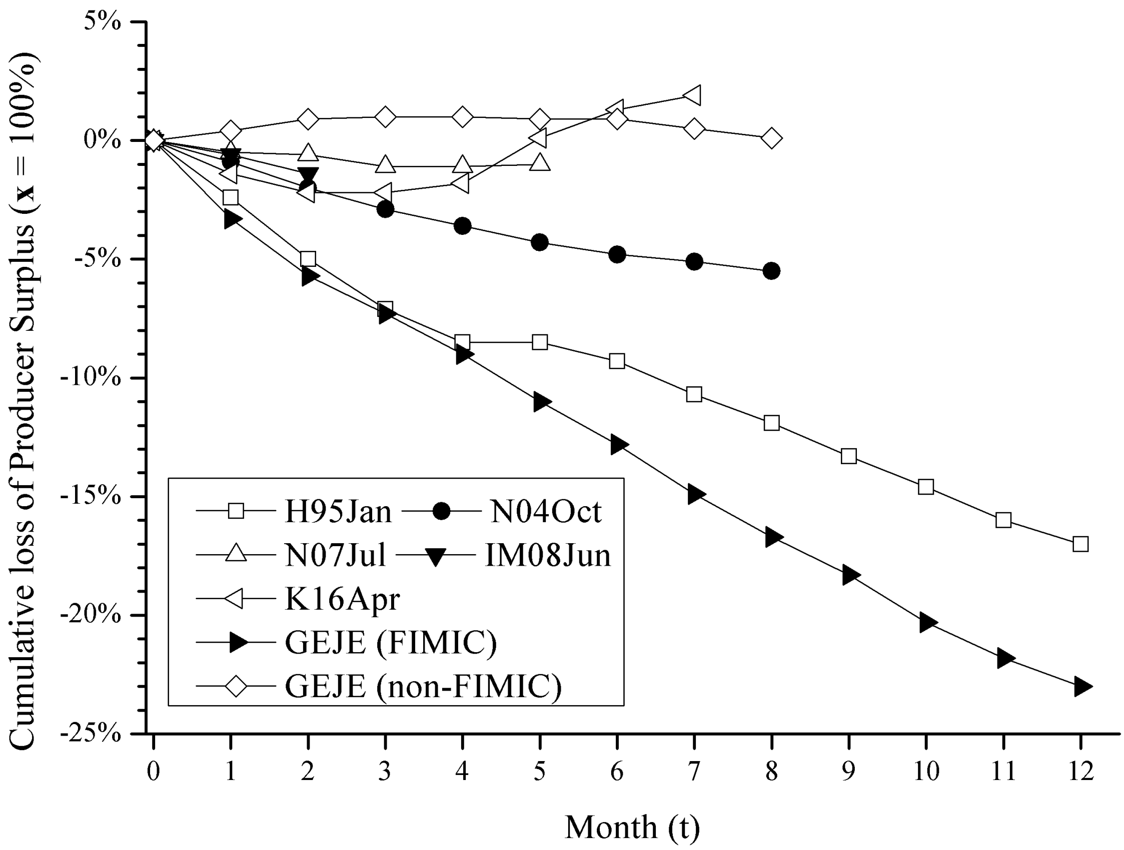

Fig. S17. Cumulative loss of producer surplus (initial production is 100%)
Note: See Table V.

Tables

Table S1. Summary of Data Necessary to Estimate Total Output Vectors (Park, 2009, Table 3, p.22)

Consumption Sector	Oil-Refinery Product Type	q^{oil}	p^{oil}	$\bar{\varepsilon}_p^{oil}$	π^{oil}	Δq^{oil}	W	Δp^{oil}	$W\Delta p^{oil}$
Transportation	Finished Motor Gasoline	263272550	69.528	−0.0334	−0.000008	−37750	0.2696	0.298	0.0804
	Kerosene-Type Jet Fuel	48463714	65.382	−0.0017	−0.000792	−23989	0.1713	18.993	3.2543
	Distillate Fuel Oil	89976381	67.920	−0.0058	−0.000129	−42582	0.3041	5.504	1.6740
	Residual Fuel Oil	6732933	39.336	−0.0058	−0.001000	−4008	0.0286	4.009	0.1148
Residential	Distillate Fuel Oil	12403498	67.920	−0.0997	−0.000055	−5870	0.0419	0.322	0.0135
Commercial	Distillate Fuel Oil	7037068	67.920	−0.4135	−0.000023	−3330	0.0238	0.078	0.0018
	Propane	33689621	41.412	−0.4135	−0.000003	−8493	0.0607	0.025	0.0015
	Residual Fuel Oil	1331172	39.336	−0.4135	−0.000071	−792	0.0057	0.057	0.0003
Industrial	Distillate Fuel Oil	13083732	67.920	−0.2018	−0.000026	−6192	0.0442	0.159	0.0070
	Residual Fuel Oil	11764067	39.336	−0.2018	−0.000017	−7002	0.0500	0.116	0.0058
Total		487754736				−140008	1.0000		5.1534
Unit		Barrel (B)	\$/B			1000B		\$/B	\$/B

Notes: Source: Park (2009, Table 3, p.22). "1) The classifications between consumption sector and oil-refinery product type are available at http://www.eia.doe.gov/emeu/states/sep_use/notes/use_petrol.pdf and 2003 percentages of 'Adjusted Sales of Fuel Oil by End Use' from http://tonto.eia.doe.gov/dnav/pet/pet_cons_top.asp were used to distribute 'Distillate' and 'Residual' Fuel Oil to the consumption sectors. 2) $W_c = \Delta q_c^{oil} / \sum_c \Delta q_c^{oil}$, where subscript c denotes Consumption Sector."

Table S2. Total Impacts via Price-sensitive Supply-driven USIO Model (Park, 2009, Table 4, p.23)

USC Sector	Total Price Increase	Proportion	Total Impact ($M.)
USC1	0.0092	0.084%	−1.29
USC2	0.0105	0.096%	−1.47
USC3	0.0087	0.080%	−1.22
USC4	0.0089	0.081%	−1.24
USC5	0.0077	0.070%	−1.07
USC6	0.0780	0.710%	−10.92
USC7	0.0000	0.000%	−0.01
USC8	0.6115	5.570%	−85.61
USC9	0.1724	1.570%	−24.13
USC10	7.1545	65.171%	−1001.69
USC11	0.2088	1.902%	−29.23
USC12	0.0021	0.019%	−0.29
USC13	0.2882	2.625%	−40.34
USC14	0.0766	0.697%	−10.72
USC15	0.0735	0.670%	−10.29
USC16	0.0421	0.384%	−5.90
USC17	0.0605	0.551%	−8.47
USC18	0.0600	0.546%	−8.40
USC19	0.0129	0.118%	−1.81
USC20	0.0576	0.524%	−8.06
USC21	0.0905	0.825%	−12.67
USC22	0.0895	0.815%	−12.53
USC23	0.0717	0.653%	−10.04
USC24	0.0221	0.201%	−3.09
USC25	0.0481	0.438%	−6.73
USC26	0.0085	0.077%	−1.19
USC27	0.0108	0.099%	−1.51
USC28	0.0115	0.105%	−1.61
USC29	0.0119	0.109%	−1.67
USC30	0.1662	1.514%	−23.26
USC31	0.0088	0.080%	−1.23
USC32	0.1339	1.220%	−18.75
USC33	0.1719	1.566%	−24.06
USC34	0.1064	0.969%	−14.89
USC35	0.0142	0.129%	−1.98
USC36	0.0464	0.422%	−6.49
USC37	0.0535	0.487%	−7.48
USC38	0.1555	1.416%	−21.77
USC39	0.0921	0.839%	−12.89
USC40	0.1819	1.657%	−25.46
USC41	0.0914	0.832%	−12.79
USC42	0.0171	0.156%	−2.39
USC43	0.0032	0.029%	−0.45
USC44	0.0711	0.648%	−9.95
USC45	0.0239	0.218%	−3.34
USC46	0.0082	0.075%	−1.15
USC47	0.3244	2.955%	−45.42
TOTAL	10.9780	100.000%	−1537.01

Note: Source: Park (2009, Table 4, p.23). "Price increases refer to the units in which each sector's outputs are denominated."

Table S3. Comparison between IOA, this study, and CGE

Items	IOA	This study and Park (2007)	CGE
Price and quantity	· Price (model) and quantity (model) are independent with each other	· Supply quantity is exogenous (i.e., supply constraint) · Price is endogenous by price elasticity of demand via supply constraint	· Price and quantity are elastic with each other · Determined simultaneously by utility function to be theoretically consistent
Endogenous sectors (intermediate demand and input)	· Supply and demand are balanced · Based on technical coefficients	(same as IOA)	· Supply and demand are balanced as in IOA · Profit maximization is modelled
Labor and capital (primary inputs of value added)	· Exogenous · Supply and demand may be unbalanced · Free to use	(same as IOA)	· Endogenous · Supply and demand are balanced by corporate utility function (i.e., profit maximization)
Other value added (e.g., investment depreciation)	(ditto)	(same as IOA)	· Exogenous or endogenous, depending on the model setting
Household (in final demand)	(ditto)	(same as IOA)	· Supply and demand are balanced endogenously by utility function (utility maximization)
Government and others (e.g., investment) (in final demand)	(ditto)	(same as IOA)	Exogenous or endogenous, depending on the model setting
Export (or import) in final demand (or external item)	(ditto)	(same as IOA)	(ditto)
Required data	IO table	· IO table · Price elasticity of demand · Supply constraint	· SAM (usually made from IO table) · Other values (if needed) such as price elasticity of demand
Scalability	· Yes · IOA does not matter how many sectors are included · Calculated by spreadsheet (Excel)	(same as IOA)	· No · More sectors, more computational burden · Computational problem is highly non-linear, requiring nonlinear solver (e.g., GAMS)

Table S4. Industry identification numbers

IO id	Industry Name (IO)	IIP id
1	Agriculture, forestry and fishery	—
2	Metallic ores	26
3	Non-metallic ores	26
4	Coal mining, crude petroleum and natural gas	26
5	Food and Tobacco	18
6	Beverage	18
7	Textile products	17
8	Wearing apparel and other textile products	17
9	Timber and wooden products	24
10	Furniture and fixtures	22
11	Pulp, paper, paperboard, building paper	16
12	Paper products	16
13	Publishing, printing	23
14	Chemical fertilizer	13
15	Basic inorganic chemical products	13
16	Basic organic chemical products	13
17	Organic chemical products	13
18	Synthetic resins	15
19	Synthetic fibers	15
20	Final chemical products	13
21	Medicaments	13
22	Petroleum refinery products	13
23	Coal products	13
24	Plastic products	15
25	Rubber products	20
26	Glass and glass products	12
27	Cement and cement products	12
28	Pottery, china and earthenware	12
29	Other ceramic, stone and clay products	12
30	Pig iron and crude steel	3
31	steel products	3
32	Cast and forged steel products	3
33	Other iron or steel products	3
34	Non-ferrous metals	4
35	Non-ferrous metal products	4
36	Metal products for construction and architecture	5
37	Other metal products	5
38	General industrial machinery	6
39	Special industrial machinery	6
40	Other general machines	6
41	Machinery for office and service industry	6
42	Industrial electric equipment	7
43	Applied electrical equipment and electrical measuring instruments	7
44	Other electric equipment	7
45	Household electric and electric applications	7
46	Communication equipment	8
47	Electric computing equipment and accessory equipment	8
48	Semiconductor devices and integrated circuits	9
49	Other electrical equipment	9
50	Passenger motor cars	10
51	Other cars	10
52	Motor vehicle parts and accessories	10
53	Other transportation equipment	10
54	Precision instruments	10

55	Miscellaneous manufacturing products	25
56	Reuse and recycling	—
57	Building construction and repair of construction	—
58	Public construction	—
59	Other civil engineering and construction	—
60	Electricity	—
61	Gas supply and heat supply	—
62	Water supply and waste management services	—
63	Commerce	—
64	Financial and insurance	—
65	Real estate agencies and rental services	—
66	House rent	—
67	Transport	—
68	Communication	—
69	Broadcasting	—
70	Information services	—
71	Internet-based services	—
72	Image information production and distribution industry	—
73	Public administration	—
74	Education and Research	—
75	Medical service, health and social security and nursing care	—
76	Advertising and survey	—
77	Goods rental and leasing services	—
78	Other business services	—
79	Personal services	—
80	Activities not elsewhere classified	—

Notes: This table shows 80 industries for the IOA. IIP id denotes industry codes of IIP, which are used for calculating production capacity (survival coefficients). For the 26 non-mining and manufacturing industry sectors (ID 1 and 56 to 80), there are no IIP ids; thus, these sectors are essentially excluded herein.

Table S5. Industries of IIP for substitution numbers

IIP id	IIP Industry name	Substitute IIP id if there is missing value
1	Mining and manufacturing (Total)	2
2	Manufacturing (Total)	1
3	Iron and steel	2
4	Non-ferrous metals	2
5	Fabricated metals	2
6	General machinery	2
7	Electrical machinery	2
8	Information and communication electronics equipment	2
9	Electronic parts and devices	2
10	Transport equipment	2
11	Precision instruments	2
12	Ceramics, stone and clay products	2
13	Chemicals	2
14	Petroleum and coal products	2
15	Plastic products	2
16	Pulp, paper and paper products	2
17	Textiles	2
18	Foods and tobacco	2
19	Other (Total)	2
20	Rubber products	19
21	Leather products	19
22	Furniture	19
23	Printing	19
24	Wood and wood products	19
25	Other products	19
26	Mining (Total)	1

Notes: This table shows the industry identification numbers of IIP (IIP id). This table corresponds to Table S2 by IIP id. Missing values can occur because certain prefectures often do not disclose indices for each industry; where this is the case, we substitute related IIP id as shown in the right column.

Table S6. Production (**x**) and final demand (**y**) at the monthly level in each prefecture (unit: B JPY)

		(1)	(2)	(3)	(4)	(5)	(6)
#	Prefecture	**x**	**x**	**x**	**y**	**y**	**y**
	(Sectors)	All sectors	54 industrial sectors	26 other sectors	All sectors	54 industrial sectors	26 other sectors
1	Hokkaido	2,827	520 (18%)	2,307 (82%)	1,744	206 (12%)	1,538 (88%)
2	Aomori	625	112 (18%)	513 (82%)	413	54 (13%)	359 (87%)
3	Iwate	696	204 (29%)	492 (71%)	438	108 (25%)	330 (75%)
4	Miyagi	1,295	321 (25%)	974 (75%)	775	147 (19%)	628 (81%)
5	Akita	538	123 (23%)	415 (77%)	337	56 (17%)	281 (83%)
6	Yamagata	653	240 (37%)	413 (63%)	415	142 (34%)	273 (66%)
7	Fukushima	1,299	460 (35%)	840 (65%)	739	237 (32%)	502 (68%)
8	Ibaraki	2,099	1,013 (48%)	1,086 (52%)	1,096	398 (36%)	698 (64%)
9	Tochigi	1,412	703 (50%)	709 (50%)	854	393 (46%)	461 (54%)
10	Gunma	1,351	644 (48%)	708 (52%)	758	314 (42%)	443 (58%)
11	Saitama	3,280	1,146 (35%)	2,134 (65%)	1,964	554 (28%)	1,410 (72%)
12	Chiba	3,242	1,116 (34%)	2,127 (66%)	1,785	371 (21%)	1,414 (79%)
13	Tokyo	12,179	879 (7%)	11,300 (93%)	7,148	347 (5%)	6,801 (95%)
14	Kanagawa	5,007	1,741 (35%)	3,265 (65%)	3,050	839 (28%)	2,211 (72%)
15	Niigata	1,401	400 (29%)	1,001 (71%)	832	172 (21%)	659 (79%)
16	Toyama	742	321 (43%)	421 (57%)	394	116 (29%)	279 (71%)
17	Ishikawa	693	194 (28%)	500 (72%)	441	108 (24%)	333 (76%)
18	Fukui	519	164 (32%)	355 (68%)	298	76 (25%)	222 (75%)
19	Yamanashi	528	199 (38%)	329 (62%)	338	114 (34%)	223 (66%)
20	Nagano	1,427	515 (36%)	912 (64%)	872	300 (34%)	572 (66%)
21	Gifu	1,169	450 (39%)	719 (61%)	653	174 (27%)	479 (73%)
22	Shizuoka	2,847	1,354 (48%)	1,493 (52%)	1,543	647 (42%)	896 (58%)
23	Aichi	6,589	3,105 (47%)	3,484 (53%)	3,548	1,441 (41%)	2,106 (59%)
24	Mie	1,488	838 (56%)	651 (44%)	794	373 (47%)	421 (53%)
25	Shiga	970	505 (52%)	465 (48%)	568	250 (44%)	317 (56%)
26	Kyoto	1,367	385 (28%)	982 (72%)	866	208 (24%)	658 (76%)
27	Osaka	5,741	1,351 (24%)	4,390 (76%)	3,134	532 (17%)	2,601 (83%)
28	Hyogo	3,030	1,179 (39%)	1,851 (61%)	1,812	558 (31%)	1,254 (69%)
29	Nara	564	175 (31%)	389 (69%)	379	91 (24%)	288 (76%)
30	Wakayama	576	232 (40%)	345 (60%)	326	93 (29%)	233 (71%)
31	Tottori	307	91 (30%)	216 (70%)	195	44 (22%)	151 (78%)

32	Shimane	377	90 (24%)	287 (76%)	247	47 (19%)	201 (81%)
33	Okayama	1,381	683 (49%)	698 (51%)	731	276 (38%)	455 (62%)
34	Hiroshima	1,989	763 (38%)	1,226 (62%)	1,101	317 (29%)	783 (71%)
35	Yamaguchi	1,045	504 (48%)	541 (52%)	564	214 (38%)	350 (62%)
36	Tokushima	429	139 (32%)	290 (68%)	255	61 (24%)	194 (76%)
37	Kagawa	597	194 (32%)	403 (68%)	318	77 (24%)	242 (76%)
38	Ehime	832	299 (36%)	533 (64%)	470	115 (24%)	355 (76%)
39	Kochi	324	49 (15%)	275 (85%)	218	21 (10%)	197 (90%)
40	Fukuoka	2,844	707 (25%)	2,136 (75%)	1,693	356 (21%)	1,336 (79%)
41	Saga	431	132 (31%)	299 (69%)	266	72 (27%)	194 (73%)
42	Nagasaki	630	120 (19%)	510 (81%)	414	66 (16%)	348 (84%)
43	Kumamoto	840	226 (27%)	614 (73%)	511	92 (18%)	419 (82%)
44	Oita	785	344 (44%)	441 (56%)	416	120 (29%)	296 (71%)
45	Miyazaki	548	123 (22%)	425 (78%)	352	67 (19%)	285 (81%)
46	Kagoshima	796	159 (20%)	637 (80%)	485	71 (15%)	414 (85%)
47	Okinawa	481	49 (10%)	432 (90%)	322	19 (6%)	302 (94%)
--	Monthly total	80,793	25,263 (31%)	55,530 (69%)	46,870	11,455 (24%)	35,415 (76%)
--	Yearly total	969,519	303,157 (31%)	666,362 (69%)	562,437	137,457 (24%)	424,980 (76%)

Note: Monthly values are calculated by dividing annual values by 12.

Table S7. Initial monthly production of each prefecture and initial social, consumer, and producer surpluses (unit: T JPY)

Area	Hyogo (H95Jan)	Niigata (N04Oct) (N07Jul)	Iwate&Miyagi (IM08Jun)	Kumamoto (K16Apr)	FIMIC (GEJE)	Non-FIMIC (GEJE)	Japan
All sectors							
Production (x)	3.0	1.4	2.0	0.8	8.6	72.2	80.8
	(100%)	(100%)	(100%)	(100%)	(100%)	(100%)	(100%)
Consumer surplus	3.8	2.1	2.8	1.2	13.2	90.4	103.6
	(126%)	(150%)	(141%)	(141%)	(153%)	(125%)	(128%)
Producer surplus	1.5	0.7	1.0	0.4	4.3	36.1	40.4
	(50%)	(50%)	(50%)	(50%)	(50%)	(50%)	(50%)
Social surplus	5.3	2.8	3.8	1.6	17.5	126.5	144.0
	(176%)	(200%)	(191%)	(191%)	(203%)	(175%)	(178%)
Mining and Manufacturing sectors (IIP)							
Production (x)	1.2	0.4	0.5	0.2	3.1	22.1	25.3
	(100%)	(100%)	(100%)	(100%)	(100%)	(100%)	(100%)
Consumer surplus	1.4	0.5	0.6	0.2	3.5	23.0	26.6
	(116%)	(119%)	(112%)	(105%)	(114%)	(104%)	(105%)
Producer surplus	0.6	0.2	0.3	0.1	1.6	11.1	12.6
	(50%)	(50%)	(50%)	(50%)	(50%)	(50%)	(50%)
Social surplus	2.0	0.7	0.9	0.4	5.1	34.1	39.2
	(166%)	(169%)	(162%)	(155%)	(164%)	(154%)	(155%)

Table S8. Production (**x**) and final demand (**y**) at the monthly level in 80 sectors (unit: B JPY)

IO id	Sector name	**x**	**y**
1	Agriculture, forestry and fishery	1,092	346
2	Metallic ores	2	0
3	Non-metallic ores	73	5
4	Coal mining, crude petroleum and natural gas	10	0
5	Food and Tobacco	2,366	1,599
6	Beverage	617	470
7	Textile products	189	61
8	Wearing apparel and other textile products	191	127
9	Timber and wooden products	211	12
10	Furniture and fixtures	203	54
11	Pulp, paper, paperboard, building paper	373	30
12	Paper products	278	43
13	Publishing, printing	528	27
14	Chemical fertilizer	27	2
15	Basic inorganic chemical products	156	28
16	Basic organic chemical products	220	31
17	Organic chemical products	455	132
18	Synthetic resins	232	61
19	Synthetic fibers	39	13
20	Final chemical products	532	255
21	Medicaments	540	93
22	Petroleum refinery products	1,166	446
23	Coal products	95	9
24	Plastic products	909	151
25	Rubber products	253	89
26	Glass and glass products	144	40
27	Cement and cement products	255	11
28	Pottery, china and earthenware	62	19
29	Other ceramic, stone and clay products	145	36
30	Pig iron and crude steel	567	16
31	steel products	1,125	266
32	Cast and forged steel products	149	9
33	Other iron or steel products	166	8
34	Non-ferrous metals	173	29
35	Non-ferrous metal products	422	88
36	Metal products for construction and architecture	393	24
37	Other metal products	690	127
38	General industrial machinery	777	507
39	Special industrial machinery	1,096	899
40	Other general machines	329	212
41	Machinery for office and service industry	352	274
42	Industrial electric equipment	584	337
43	Applied electrical equipment and electrical measuring instruments	245	220
44	Other electric equipment	312	187
45	Household electric and electric applications	220	193
46	Communication equipment	649	588
47	Electric computing equipment and accessory equipment	345	329
48	Semiconductor devices and integrated circuits	513	270
49	Other electrical equipment	960	307
50	Passenger motor cars	1,070	998

51	Other cars	322	310
52	Motor vehicle parts and accessories	2,371	628
53	Other transportation equipment	450	274
54	Precision instruments	317	255
55	Miscellaneous manufacturing products	394	256
56	Reuse and recycling	73	19
57	Building construction and repair of construction	3,210	2,570
58	Public construction	1,325	1,325
59	Other civil engineering and construction	628	628
60	Electricity	1,497	428
61	Gas supply and heat supply	275	122
62	Water supply and waste management services	719	280
63	Commerce	8,049	5,046
64	Financial and insurance	3,863	1,406
65	Real estate agencies and rental services	1,829	1,190
66	House rent	4,111	4,111
67	Transport	4,118	1,660
68	Communication	1,347	632
69	Broadcasting	297	87
70	Information services	1,520	838
71	Internet-based services	106	20
72	Image information production and distribution industry	608	142
73	Public administration	3,089	2,998
74	Education and Research	3,096	2,079
75	Medical service, health and social security and nursing care	4,616	4,421
76	Advertising and survey	814	181
77	Goods rental and leasing services	995	116
78	Other business services	3,383	583
79	Personal services	4,392	4,161
80	Activities not elsewhere classified	478	27
—	Monthly total	80,793	46,870
—	Yearly total	969,519	562,437

Table S9. Sample size of each IIP for production capacity

IIP id	H95Jan	N04Oct	N07Jul	IM08Jun	K16Apr	GEJE: FIMIC	GEJE: non-FIMIC
(# of prefectures)	(1)	(1)	(1)	(2)	(1)	(5)	(42)
#1	1	1	1	2	1	5	34
#2	1	1	1	2	1	5	38
#3	1	1	1	2	1	5	42
#4	1	1	1	2	1	5	36
#5	1	1	1	2	1	5	41
#6	1	1	0	0	1	4	13
#7	1	1	1	2	1	2	11
#8	0	1	1	2	0	4	26
#9	0	1	1	2	1	5	30
#10	1	1	1	2	1	5	39
#11	1	1	0	0	0	3	4
#12	1	1	1	2	1	5	42
#13	1	1	1	2	1	5	37
#14	1	0	0	1	0	3	13
#15	1	1	1	2	1	5	41
#16	1	1	1	2	0	5	39
#17	1	1	1	2	1	5	41
#18	1	1	1	2	1	5	42
#19	1	1	1	2	0	5	39
#20	1	0	0	0	1	2	23
#21	1	0	0	0	0	0	10
#22	1	1	0	0	0	2	23
#23	1	0	0	0	0	5	19
#24	1	1	1	0	1	5	36
#25	1	1	1	0	1	5	20
#26	0	1	1	1	1	4	26

Notes: This table shows IIP sample sizes for production capacity. IIP data used herein cover 26 sectors and may have missing values, depending on the prefectural statistics. Each of the earthquakes affected a different number of prefectures: 1 prefecture for H95Jan, N04Oct, N07Jul, and K16Apr; 2 prefectures for IM08Jun; and 5 (FIMIC) and 42 prefectures (non-FIMIC) for GEJE. Therefore, the maximum sample size of each IIP id should be 1 for H95Jan, N04Oct, N07Jul, and K16Apr, 2 for IM08Jun, 5 for FIMIC, and 42 for non-FIMIC. Finally, 0 denotes that no IIP data are used.

Table S10. Descriptive statistics for JIP database

Variable	Obs	Average	Std. Dev.	Min	Max
Real gross output (q) (million JPY in 2011)	2,194	9,526,640	11437374	94,677	76,655,035
Nominal gross output (million JPY)	2,194	9,656,146	11498946	110,203	75,516,116
Deflator (p)	2,194	1.047	0.309	0.359	4.780
ln(q)	2,194	15.459	1.182	11.458	18.155
ln(p)	2,194	0.017	0.228	-1.024	1.564

Note: This data comes from the JIP database 2018.

Table S11. Regression results of the price elasticity of demand (ε)

No.	JIP Industry Name	(1) Coef. (ε)	(2) Std. Err.	(3) Real gross output (2005; T JPY)	(4) JIP Industry group (#1–100)	(5) IIP Industry group (#1–80)
1	Agriculture	–0.105	(0.559)	9.7	1–4	1
2	Agricultural services	–1.112	(1.453)	0.7	1–4	1
3	Forestry	1.014*	(0.608)	0.4	1–4	1
4	Fisheries	0.569	(0.750)	1.7	1–4	1
5	Mining	–1.321**	(0.637)	1.2	5–16	2–8,11,12,19
6	Livestock products	–0.337	(0.840)	4.9	5–16	2–8,11,12,19
7	Seafood products	–2.674***	(0.755)	3.7	5–16	2–8,11,12,19
8	Flour and grain mill products	–0.764	(0.645)	1.4	5–16	2–8,11,12,19
9	Miscellaneous foods and related products	1.390	(0.925)	13.1	5–16	2–8,11,12,19
10	Beverages	3.385**	(1.690)	7.8	5–16	2–8,11,12,19
11	Prepared animal foods and organic fertilizers	–0.051	(0.578)	1.0	5–16	2–8,11,12,19
12	Tobacco	–1.358**	(0.574)	3.6	5–16	2–8,11,12,19
13	Textile products (except chemical fibers)	–5.591***	(0.912)	4.6	5–16	2–8,11,12,19
14	Chemical fibers	–3.048***	(0.625)	0.7	5–16	2–8,11,12,19
15	Pulp, paper, and coated and glazed paper	–1.498**	(0.731)	5.3	5–16	2–8,11,12,19
16	Paper products	–1.987**	(0.818)	3.7	5–16	2–8,11,12,19
17	Chemical fertilizers	–0.920	(0.601)	0.7	17–28	14–18, 20-23, 26–29
18	Basic inorganic chemicals	–0.872	(0.596)	1.9	17–28	14–18, 20-23, 26–29
19	Basic organic chemicals	0.359	(0.565)	3.4	17–28	14–18, 20-23, 26–29
20	Organic chemicals	–0.716	(0.580)	12.0	17–28	14–18, 20-23, 26–29
21	Pharmaceutical products	–1.439**	(0.603)	5.7	17–28	14–18, 20-23, 26–29
22	Miscellaneous chemical products	0.062	(1.372)	7.0	17–28	14–18, 20-23, 26–29
23	Petroleum products	–0.195	(0.564)	21.4	17–28	14–18, 20-23, 26–29
24	Coal products	–0.312	(0.564)	2.2	17–28	14–18, 20-23, 26–29
25	Glass and its products	–0.042	(0.613)	1.5	17–28	14–18, 20-23, 26–29
26	Cement and its products	–2.816***	(0.707)	3.5	17–28	14–18, 20-23, 26–29
27	Pottery	0.721	(0.645)	0.7	17–28	14–18, 20-23, 26–29
28	Miscellaneous ceramic, stone and clay products	–0.855	(0.690)	2.0	17–28	14–18, 20-23, 26–29
29	Pig iron and crude steel	0.575	(0.572)	23.6	29–34	30–37

30	Miscellaneous iron and steel	–0.475	(0.581)	10.0	29–34	30–37
31	Smelting and refining of non-ferrous metals	0.129	(0.565)	3.3	29–34	30–37
32	Non-ferrous metal products	–0.068	(0.587)	6.3	29–34	30–37
33	Fabricated constructional and architectural metal products	–2.094***	(0.710)	5.0	29–34	30–37
34	Miscellaneous fabricated metal products	–1.665**	(0.731)	8.3	29–34	30–37
35	General-purpose machinery	–0.275	(1.424)	11.0	35–48	38–49
36	Production machinery	0.087	(1.206)	15.4	35–48	38–49
37	Office and service industry machines	–0.478	(0.590)	4.0	35–48	38–49
38	Miscellaneous business oriented machinery	–0.956	(0.732)	3.6	35–48	38–49
39	Ordnance	–8.378***	(0.832)	0.4	35–48	38–49
40	Semiconductor devices and integrated circuits	–0.717	(0.562)	3.3	35–48	38–49
41	Miscellaneous electronic components and devices	–0.729	(0.569)	9.0	35–48	38–49
42	Electrical devices and parts	0.565	(0.879)	7.5	35–48	38–49
43	Household electric appliances	–0.497	(0.568)	2.3	35–48	38–49
44	Electronic equipment and electric measuring instruments	–0.367	(0.578)	2.3	35–48	38–49
45	Miscellaneous electrical machinery equipment	–0.479	(0.587)	3.1	35–48	38–49
46	Image and audio equipment	–0.181	(0.563)	2.5	35–48	38–49
47	Communication equipment	–0.454	(0.566)	3.7	35–48	38–49
48	Electronic data processing machines, digital and analog computer equipment and accessories	–0.057	(0.561)	2.7	35–48	38–49
49	Motor vehicles (including motor vehicles bodies)	–0.297	(0.835)	23.2	49–51	50–53
50	Motor vehicle parts and accessories	–4.216***	(0.843)	23.6	49–51	50–53
51	Other transportation equipment	0.176	(0.789)	5.4	49–51	50–53
52	Printing	1.814**	(0.776)	5.9	52–59	9,10,13,24,25,54,55
53	Lumber and wood products	–1.841**	(0.731)	2.7	52–59	9,10,13,24,25,54,55
54	Furniture and fixtures	–6.456***	(0.915)	2.5	52–59	9,10,13,24,25,54,55
55	Plastic products	–0.136	(0.894)	11.2	52–59	9,10,13,24,25,54,55
56	Rubber products	–0.928	(0.934)	3.4	52–59	9,10,13,24,25,54,55
57	Leather and leather products	–7.406***	(0.962)	0.5	52–59	9,10,13,24,25,54,55
58	Watches and clocks	1.672***	(0.608)	0.3	52–59	9,10,13,24,25,54,55

59	Miscellaneous manufacturing industries	3.148***	(0.810)	4.1	52–59	9,10,13,24,25,54,55
60	Electricity	–0.333	(0.653)	16.7	60–65	60–62
61	Gas, heat supply	0.621	(0.589)	3.6	60–65	60–62
62	Waterworks	–0.504	(0.735)	3.1	60–65	60–62
63	Water supply for industrial use	–0.721	(0.829)	0.1	60–65	60–62
64	Sewage disposal	1.226	(1.265)	2.6	60–65	60–62
65	Waste disposal	0.424	(0.836)	5.3	60–65	60–62
66	Construction	–1.757	(1.159)	41.5	66,67,89	56–59
67	Civil engineering	–3.584***	(0.950)	24.6	66,67,89	56–59
68	Wholesale	–1.073	(1.354)	76.7	68,69	63
69	Retail	–3.008***	(0.919)	38.1	68,69	63
70	Railway	–0.370	(1.532)	7.6	70–75, 88	67,77
71	Road transportation	0.286	(1.480)	20.5	70–75, 88	67,77
72	Water transportation	1.710**	(0.748)	5.8	70–75, 88	67,77
73	Air transportation	–0.845	(0.695)	4.4	70–75, 88	67,77
74	Other transportation and packing	–1.508	(1.489)	4.3	70–75, 88	67,77
75	Mail	3.066	(2.226)	1.9	70–75, 88	67,77
76	Hotels	1.264	(1.224)	6.5	76,84,85	65,66
77	Eating and drinking services	–2.042**	(0.992)	26.5	77,96–100	79,80
78	Communications	–1.898***	(0.577)	13.8	78–81,87	68–72,76
79	Broadcasting	–4.226***	(1.312)	3.6	78–81,87	68–72,76
80	Information services	–5.958***	(0.826)	18.0	78–81,87	68–72,76
81	Image information, sound information and character information production	4.298**	(2.101)	7.8	78–81,87	68–72,76
82	Finance	0.169	(0.613)	25.3	82,83	64
83	Insurance	–2.426**	(1.183)	12.9	82,83	64
84	Housing	–0.720	(1.365)	45.9	76,84,85	65,66
85	Real estate	–2.321**	(0.941)	20.8	76,84,85	65,66
86	Research	1.378	(1.113)	4.2	86,90–92	73,74,78
87	Advertising	2.857***	(0.964)	8.3	78–81,87	68–72,76
88	Rental of office equipment and goods	–0.725	(0.568)	9.3	70–75, 88	67,77
89	Automobile maintenance services	0.984	(1.077)	10.0	66,67,89	56–59
90	Other services for businesses	–6.552***	(1.078)	29.4	86,90–92	73,74,78
91	Public administration	–1.552	(0.947)	37.3	86,90–92	73,74,78
92	Education	–1.032	(0.883)	21.6	86,90–92	73,74,78

93	Medical service, health and hygiene	–2.722*	(1.629)	33.0	93–95	75
94	Social insurance and social welfare	–0.442	(0.951)	8.0	93–95	75
95	Nursing care	–9.001***	(1.099)	6.2	93–95	75
96	Entertainment	2.071*	(1.150)	10.5	77,96–100	79,80
97	Laundry, beauty and bath services	–0.141	(3.346)	6.3	77,96–100	79,80
98	Other services for individuals	3.075**	(1.333)	7.9	77,96–100	79,80
99	Membership organizations	–1.337	(1.326)	4.9	77,96–100	79,80
100	Activities not elsewhere classified	–0.844	(0.677)	3.5	77,96–100	79,80
—	Constant (for #1)	16.149***	(0.032)	—	—	—
—	Industry dummy (#2–100)	Yes	—	—	—	—
—	# of observations	2,194	—	—	—	—
—	R-squared	0.989	—	—	—	—
—	Adjusted R-squared	0.988	—	—	—	—

Notes: Columns 1 and 2 show the estimated results of a regression model. Values with and without parentheses are coefficients and standard error, respectively. ***, **, and * denote statistically significant levels of 1%, 5%, and 10%, respectively. Column 3 shows real gross output as of 2005 to calculate weighted average price elasticity in 17 summarized groups (see Table II). Columns 4 and 5 indicate the JIP Industry group (#1–100) and IIP Industry group (#1–80), respectively, for creating the weighted average groups.

Table S12. Earthquake damage estimates from previous studies: H95Jan and GEJE

#	Estimation	Direct damage	Indirect damage	(This study)
H95Jan	Hyogo prefectural government and National Land Agency, Japan[27]	9,926.8B JPY for damage to capital stock	–	(The cumulative loss of social surplus [Δss] is 1.25T JPY for 12 months [Δcs is 1.45T JPY; Δps is –0.2T JPY])
H95Jan	Toyoda and Kouchi (1997)	13,268.2B (=9,926.8B+3,341.4B) JPY in total; 5,930B JPY in total in 10 cities and 10 towns; 1,510B JPY for industrial sectors in 10 cities and 10 towns.	7,230B JPY in total in 10 cities and 10 towns (for 1 year); 1,203.1B JPY for industrial sectors in 10 cities and 10 towns (for 1 year).	
GEJE	The national government (Hayashi, 2012)	Approximately 16,900B JPY (or 3.5% of GDP)	–	(The cumulative loss of social surplus [Δss] is 16.94T JPY until the temporal recovery [7.83T JPY to FIMIC at t=37; 9.11T JPY to non-FIMIC prefectures at t=8])
GEJE	Hayashi (2012)	Approximately 30T JPY (or 6% of GDP)	Approximately 10T JPY for the annual gross regional product in Fukushima, and 100T JPY in total for 10 years. This study estimates approximately 24T JPY for 10 years only in industrial sectors.	