A Resource Allocation Model for Estimating Indirect Earthquake Damage: The Case of a Tokyo-Epicentered Earthquake

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Abstract

According to forecasts, there is a 70% probability that a “Tokyo-epicentered earthquake” with a magnitude of 7 originating in the southern Kanto area will occur within the next 30 years. While the extent of direct damage from such an earthquake would likely exceed that of the Great East Japan Earthquake of March 2011, the indirect economic damage would be of a different scale as Tokyo is at the heart of the Japanese economy. Several methodologies can be considered as ways to estimate indirect damage from an earthquake. The first methodology involves applying a traditional input–output analysis model to direct damage. The second methodology consists of assuming the non-substitutability of intermediate inputs and reverse calculating how much production would decline due to earthquake-induced bottlenecks in intermediate inputs. The third comprises estimating the production function using capital and labor as explanatory variables and then estimating the decline in production value from the amount of damage incurred by employed persons and capital stock. The fourth methodology consists of formulating some scenarios for declines in production due to the earthquake and using mathematical programming to reallocate resources.

Among these, empirical research has provided only a few examples of the fourth methodology. Therefore, this paper will introduce this method and attempt to estimate the indirect damage from a feared “Tokyo-epicentered earthquake” by applying this method to the 2015 input–output tables for the Tokyo Metropolis. Because this estimation method incorporates supply constraints on production goods, production volume is a predetermined variable, and final demand is an endogenous variable. These are the opposite of the predetermined variables of the traditional input–output analytical model.

Keywords

Tokyo-epicentered earthquake, indirect earthquake damage,
mathematical programming, resource allocation model

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1. Introduction

The Great East Japan Earthquake of March 11, 2011, caused about 22,000 deaths, and the economic damage was huge. The amount of direct damage to infrastructure and buildings is estimated to have exceeded 15 trillion yen [1] while traffic disruptions and damage to businesses caused production activity to come to a grinding halt, which also affected production activities at businesses located downstream in the production process. The distinguishing characteristic of the Great East Japan Earthquake is that these supply constraints caused a huge volume of indirect damage. Currently, there is concern that an inland earthquake [2] will occur in the southern part of the Kanto area (the Tokyo area). As the Kanto area is the center of Japanese production, distribution, and data, one can easily imagine that the occurrence of a major earthquake in this area would lead to very wide-ranging supply constraints and have an enormous impact on the Japanese economy.

Here, let us touch upon the scale of earthquake energy. Taking earthquake energy as $\boldsymbol{E}$ (in joules) and magnitude as $\boldsymbol{M}$, the correlation is $\log(E) = 4.8 + 1.5M$. Here, the logarithm is base 10. From this equation, if the difference in magnitude is 1, the difference in the logarithm will be 1.5, so the difference in the earthquake's energy will be about 30 times. In general, an earthquake with a magnitude of more than 7 is called a major earthquake, while an earthquake with a magnitude of more than 8 is called a great earthquake. The worst great earthquake in the history of recordkeeping in Japan was the Great East Japan Earthquake, which had a magnitude of 9.0. The most recent major inland earthquake in memory was the Great Hanshin Earthquake. Comparing the M9.0 Great East Japan Earthquake and the M7.3 Great Hanshin Earthquake, even though the difference in magnitude was only 1.7, in terms of earthquake energy, the Great East Japan Earthquake was 350 times stronger than the Great Hanshin Earthquake. However, more than 6,000 people died in the Great Hanshin Earthquake, which is about 30% of the total number of deaths

1 Estimates of the direct financial impact of earthquake damage include those of the Cabinet Office (2011), at about 16.9 trillion yen, and those of the Development Bank of Japan (2011), at about 16.4 trillion yen.

2 The Central Disaster Management Council (2013) forecasts a 70% probability that an earthquake centered directly under the Tokyo area will occur within the next 30 years. There are two types of earthquakes: subduction-type earthquakes, which occur at the edges of moving tectonic plates, and inland earthquakes, which occur when tectonic plates exert pressure on the earth's crust inland, causing a fault to move. The 2011 Great East Japan Earthquake was the former type, while the 1923 Great Kanto Earthquake and the 1995 Great Hanshin Earthquake were the latter type.

from the Great East Japan Earthquake. Therefore, even an earthquake with a magnitude of around 7 will inflict major damage if its epicenter is under an urban area.

Earthquake damage consists of human damage and economic damage. In addition, economic damage consists of direct damage to structures (infrastructure, buildings, and so on), as mentioned above, and indirect damage caused by the ensuing supply constraints. This paper focuses on the latter, indirect damage. Many studies have estimated indirect damage from earthquakes, and these can be roughly classified into four types.

1) Estimates that apply the Leontief model or Ghosh model of input–output analysis to direct earthquake damage (Ashiya and Jinushi (1999), Shishido et al. (2011), Nozaki et al. (2011), Shimoda and Fujikawa (2012)).
2) Estimates that assume a non-substitutable input coefficient and reverse calculate the decline in production from bottlenecks caused by lower supplies of intermediate goods due to the earthquake (Hasebe (2002), Shimoda and Fujikawa (2012)).
3) Estimates of the decline in production volume caused by a decline in capital stock using a production function (Hagiwara (1998)).
4) Plans for the reallocation of resources that formulate various scenarios for declines in production volume due to the earthquake (Nagaoka (1976), Nishizu (2003)).

To the authors' knowledge, there have not been many empirical studies of Type 4 earthquakes in Japan. Therefore, this empirical study aligns with the thinking of Type 4 to estimate indirect earthquake damage. Using input–output tables for the Tokyo Metropolis, we present a method for estimating indirect damage from a Tokyo-epicentered earthquake. Supply constraints on intermediate goods caused by earthquakes and other disasters mean that final demand will be met with fewer choices. It is, therefore, up to the policymakers to decide which of the fewer choices for final demand to select and which production goods should be allocated to intermediate goods. That is why this model is called the resource allocation model in this study.

Examples of objective functions forming the basis of policy decisions include the maximization of GDP, maximization of consumer utility, and minimization of changes from the current situation. The traditional Leontief model treats the volume of final demand as an exogenous variable and tries to find the production volume needed to meet this final demand. The resource allocation model, however, treats production volume as an exogenous variable and reverse calculates the final demand volume that this production volume can meet.

The paper is organized as follows. Section 2 discusses prior research on the resource allocation model. Section 3 describes the data used in our model. Section 4 is a report on the simulation results, and Section 5 suggests topics for future research.

2. Prior research

Nagaoka (1976) was writing at a time when the world was facing oil supply constraints due to the oil crisis. Although most economic forecasting models at that time were of the demand-pull type, they were premised on an awareness of their shortcomings. The typical input–output analytical model took final demand as an exogenous variable and computed the volume of supply needed to fulfill that demand, but this was premised on the assumption that the necessary intermediary inputs would be available. However, the oil crisis made it clear that this premise was not based on reality. Therefore, if there were shortages of intermediate inputs, the optimal allocation of such resources to each industry would have to be determined. The analytical case presented in Nagaoka (1976) posits a situation in which minimizing the change from the current situation and maximizing GDP are objective functions.

Nishizu (2003) presents cases in which linear programming is applied to input–output tables. The discussion takes the example of finding each industry's production volume in the case of minimizing the change from the current situation during a supply shortage of rare metals (Metal Economics Research Institute, Japan (2000)) and of maximizing value added by changing the import percentage of intermediate inputs, with total imports being a fixed amount (Miyazawa (2002)).

3. Data and the analytical model

3.1 Data

The target areas for our estimations of indirect damage were all 46 prefectures in Japan excluding Tokyo itself, and for our trial calculations, we used the 2015 input–output tables for the Tokyo Metropolis (basic classification). While all of Japan's 47 prefectures release input–output tables, the input–output table for Tokyo differs from those of the other prefectures in the following two respects. First, in Tokyo's input–output tables, corporate head offices are represented as a separate industry. The head offices of Japan's major corporations are concentrated in Tokyo. These Tokyo head offices handle their companies' normal business in the Tokyo area and also provide human resources, accounting, and other head office functions for branch offices in the rest of the country. Since head office functions are not a production activity specific to the Tokyo area, they are listed as a separate sector. Head office production is estimated from total head office expenses, and from this, we can calculate the product of the number of persons engaged in management activities (obtained from the Economic Census) and head office expenses per capita incurred in management activities (obtained from the Survey on Management Activities of Enterprises).[3] The input–output tables for Tokyo (basic classification) typically consist of 38 sectors: 37 sectors plus head offices.

Second, the Tokyo input–output tables are formatted as regional input–output tables for two areas, Tokyo proper and the Tokyo suburbs. Prefectural input–output tables typically treat areas outside the relevant prefecture as exogenous, so there is no way of tracking the impact that goods and services sent outside the prefecture have within the prefecture. However, it is possible to do this with the Tokyo input–output tables, which show intermediate inputs between areas.

3.2 Setting the exogenous variables

In the analytical methodology used in this paper, the determining relationship is the reverse of that in the traditional methodology used for input–output analysis. The traditional input–output analytical methodology (the equilibrium production volume determination model) uses final demand f as an exogenous variable and domestic production as an endogenous variable. Researchers will assume a change in final demand $\mathbf{f}$ and then use a Leontief inverse matrix to calculate the domestic production $\mathbf{x}$ needed to satisfy final demand.

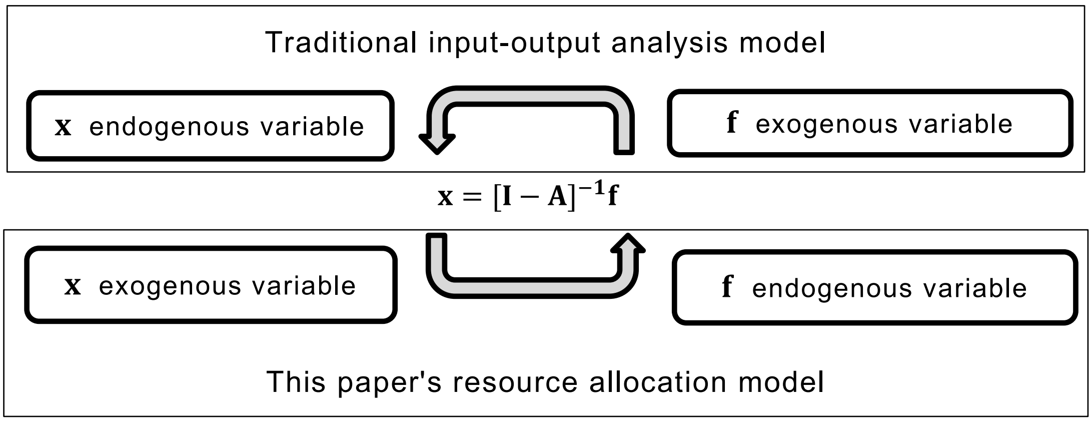

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Figure 1 The differences between the model used in this paper and the traditional input–output analytical model

3 For further details, see the Tokyo Metropolitan Government Bureau of General Affairs Statistics Division (2021).

In this paper, however, we posit that an earthquake will constrain domestic production, and we determine final demand given these production constraints. This scenario is shown in Figure 1. The major difference between the model in this paper and the traditional method of input–output analysis lies in how the exogenous variables are set. This paper takes production constraints caused by an earthquake as a given (exogenous variable) and uses a Leontief inverse matrix to find the final demand, which is an endogenous variable.

In the event of production constraints caused by an earthquake, the government will respond with some form of policy measures. Various possible policy options are posited, including maximizing the GDP after the earthquake, minimizing the changes in the GDP before and after the earthquake, maximizing household utility, and increasing domestic production by minimizing imports.

This paper assumes that policy decisions are an objective function and runs a mathematical optimization model with the aforementioned production constraints. This is used to determine the final demand as the optimal solution for the objective function.

Let us say the value of production before the earthquake is x and the value of production after the earthquake (the value of production after production constraints) is x'. Running the mathematical optimization model as described above gives us the final demand f' based on the optimal solution for policy decisions, or the objective function. This final demand f' provides information on what volume of final demand would best be allocated to which industrial sectors. In other words, we can call it a resource allocation model because it determines the allocation of final demand, the optimal solution of an objective function during production constraints. In this paper, the amount of earthquake damage is assessed as the lowest possible amount of final demand based on policy decisions made under conditions of production constraints.

These are the differences between the analytical methodology used in this paper and the traditional input–output analytical methodology. As noted, many policy options can be considered as objectives, but here we assume the two cases of (1) maximization of the GDP and (2) minimization of total changes in final demand. We use a mathematical optimization model to find the volume of final demand that would satisfy the conditions in each case. Below are descriptions of these two policy options.

3.3 The GDP maximization model

Let us assume that one policy option is to maximize the GDP following the earthquake. Domestic production declines after an earthquake because of supply constraints. We will calculate how much final demand will be needed to maximize the GDP with this decline in domestic production.

Let us describe this situation using a two-sector model. Here, the final demand is f, production is x, and the Leontief inverse matrix is [I-A]-1. Under post-earthquake domestic production constraints, the mathematical optimization model that would maximize the GDP (=GDE) is as follows:

$$Max.GDE = f_1 + f_2 \tag{1}$$

$$st.\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \geq [\mathbf{I} - \mathbf{A}]^{-1} \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \tag{2}$$

To illustrate this mathematical optimization model in a two-dimensional graph, we perform the following modification. Equation (1) is total value added, or GDP, but we can formulate final demand f as GDE. In Equation (3), aij denotes the input coefficient, and bij denotes the Leontief inverse matrix.

$$[\boldsymbol{I} - \boldsymbol{A}]^{-1} = \begin{bmatrix} 1 - a_{11} & -a_{12} \\ -a_{21} & 1 - a_{22} \end{bmatrix}^{-1} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \tag{3}$$

The mathematical optimization model consisting of Equations (A1) and (A2) above can be expressed as Equations (A4) and (A5) below.

$$Max.GDE = f_1 + f_2 \tag{4}$$

$$st.\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \geq \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \tag{5}$$

We can also rewrite Equation (5) into Equations (6) and (7) below.

From $x_1 \geq b_{11}f_1 + b_{12}f_2$, we get

$$f_2 \leq -\frac{b_{11}}{b_{12}}f_1 + \frac{x_1}{b_{12}} \tag{6}$$

From $x_2 \geq b_{21}f_1 + b_{22}f_2$, we get

$$f_2 \leq -\frac{b_{21}}{b_{22}}f_1 + \frac{x_2}{b_{22}} \tag{7}$$

Figure 2 below shows the mathematical optimization model based on the objective functions in Equation (4) and the constraints in Equations (6) and (7).

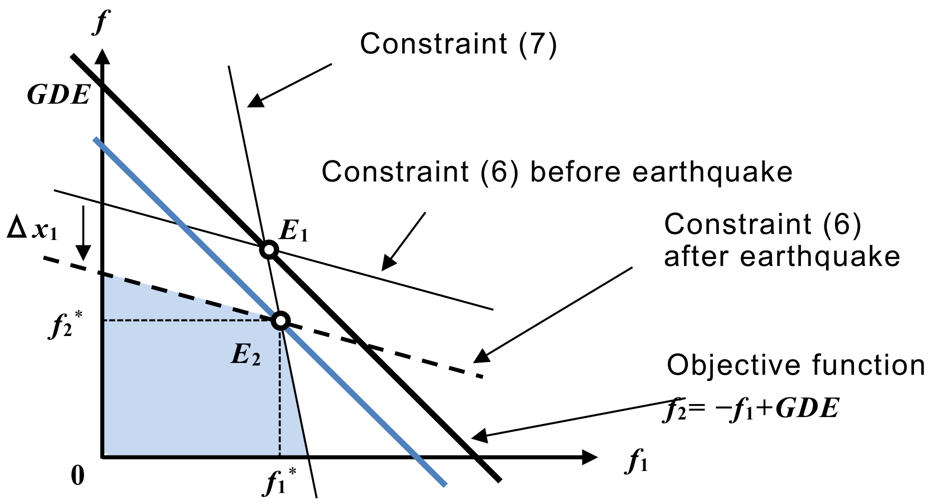

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Figure 2. Maximization of GDP using the resource allocation model

E1 is the initial equilibrium. This denotes the combination of final demand f1 and f2 that fulfills initial (pre-earthquake) domestic demand. Then, the earthquake occurs, and if the input coefficient aij remains constant when Sector 1's production x1 declines by only Δx1, Equation (6), which is the constraint equation, shifts downward, as shown by the dotted line. At the same time, Equation (7) remains constant; that is to say, input coefficient aij and Sector 2's production x2 are unchanged. In this case, the post-earthquake consumption possibility set is denoted by the shaded portion, and the new equilibrium point is E2, the intersection of Equations (6) and (7) after this shift. This new equilibrium point is created by combining final consumptions f1* and f2*, which maximize the GDP. However, the GDP is maximized on the basis of the constraints given in these two constraint equations, whereby post-earthquake production in each sector must not exceed their pre-earthquake production level.

Stated intuitively, this becomes the following. The area inside the red line is the demand possibility area before the earthquake, whereas the area inside the blue line is the demand possibility area after the earthquake. While the earthquake causes the area to shrink, the optimal solution is reached by shifting the objective function downward so that final demands f1* and f2* maximize the GDP.

3.4 The change in the final demand minimization model

Next, let us assume that one policy option is to minimize the total change in final demand in each sector due to the earthquake. Domestic production declines after the earthquake due to supply constraints. We calculate how much final demand each sector will need so that the total changes in final demand when compared with before the earthquake are minimized under these conditions of lower domestic production. As total final demand is equivalent to the GDP, this hypothesis also finds the policy option that minimizes the shock of the change in the GDP due to the earthquake.

Let us describe this situation using a two-sector model and the same variables as in 2-2. Under the post-earthquake (reduced) domestic production constraints, the mathematical optimization model that minimizes total differences in final demand before and after the earthquake is as follows 4.

$$Min. r^2 = (f_1 - f_{1o})^2 + (f_2 - f_{2o})^2 \quad (9)$$

$$st. \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \geq \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \quad (10)$$

Here, f1 and f2 denote the post-earthquake final demands for Sector 1 and Sector 2, respectively, and f10 and f20 denote the pre-earthquake final demands for Sector 1 and Sector 2, respectively. Equation (10) is the same as the previous Equation (5).

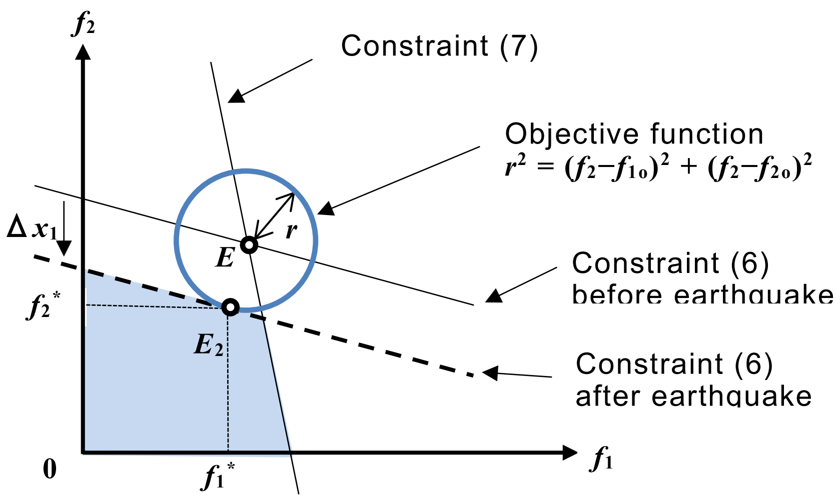

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Figure 3 Minimizing the change in final demand using the resource allocation model

Figure 3 shows a linear programming model based on the objective functions of Equation (9) and the constraint conditions of Equation (10). E1 is the initial equilibrium point. This denotes the combination of final demands f and f2 that gives the initial (pre-earthquake) domestic demand. Then, the earthquake occurs, and if the input coefficient aij is unchanged when Sector 1 demand x1 declines by only Δx1, the constraint equation, or Equation (6), shifts downward, as shown by the dotted line. At the same time, Equation (7) is unchanged; that is to say, there is no change

4 The actual calculations were standardized by dividing them by the production volume for each industry.

in input coefficient aij or Sector 2 production x2. Here, in Equation (A9), the objective coefficient is defined by the equation for the circle, which denotes the minimum change in final demand before and after the earthquake. We can also call this minimizing the radius of the circle.

The new equilibrium is point E2 on the circle's radius r, which is the minimum for Equation (6) after the shift. This new equilibrium point is the combination of final demands f1* and f2*, which constitute the minimum change in final demand before and after the earthquake. However, the minimized changes in final demand were achieved on the basis of the constraints in these two constraint equations, whereby post-earthquake production in each sector does not exceed pre-earthquake production in those same sectors.

4. Simulation

4.1 Assumptions used for estimation

Our estimates categorized the decline in production in Tokyo into two sectors: head offices and non-head offices. First, for the non-head office sector, from the Report on Prefectural (City) Accounts, we found the rate of change between fiscals 1993 and 1994 for the total product of Kobe City by industry following the Great Hanshin Earthquake. We then hypothesized that the difference between this rate of change and the nationwide rate of change was due to the impact of the earthquake. In this paper, we apply this rate of change to the rate of decline in Tokyo's prefectural production. This is illustrated in Figure 4. Moreover, for sectors that had increased, such as construction, we assumed a zero rate of decline in the Tokyo prefectural production.

For the decline in production in the head office sector, we assumed that head office functions would be a total loss but then recover within one year. In this case, we assumed that backup locations would be operating, so we set the decline in production at about 10%. According to the 2016 Economic Census for Business Activity, people working at head offices in Tokyo made up 27.1% of total head office employees in Japan, so almost 30% of head office employees are concentrated in Tokyo. This is grounds for ranking head office functions as one of Tokyo's major industries. According to a 2021 survey by the Ministry of Land, Infrastructure and Transport, 31% of companies had alternative or backup locations available for the head office divisions and departments in the event of a disaster, meaning that more than half did not have such facilities. At the same time, when classified by company size, more than half of companies with 1,000 or more employees had such facilities, so we can say that larger companies tend to have backup facilities of some sort. The aforementioned 10% decline in annual production is premised on this situation.

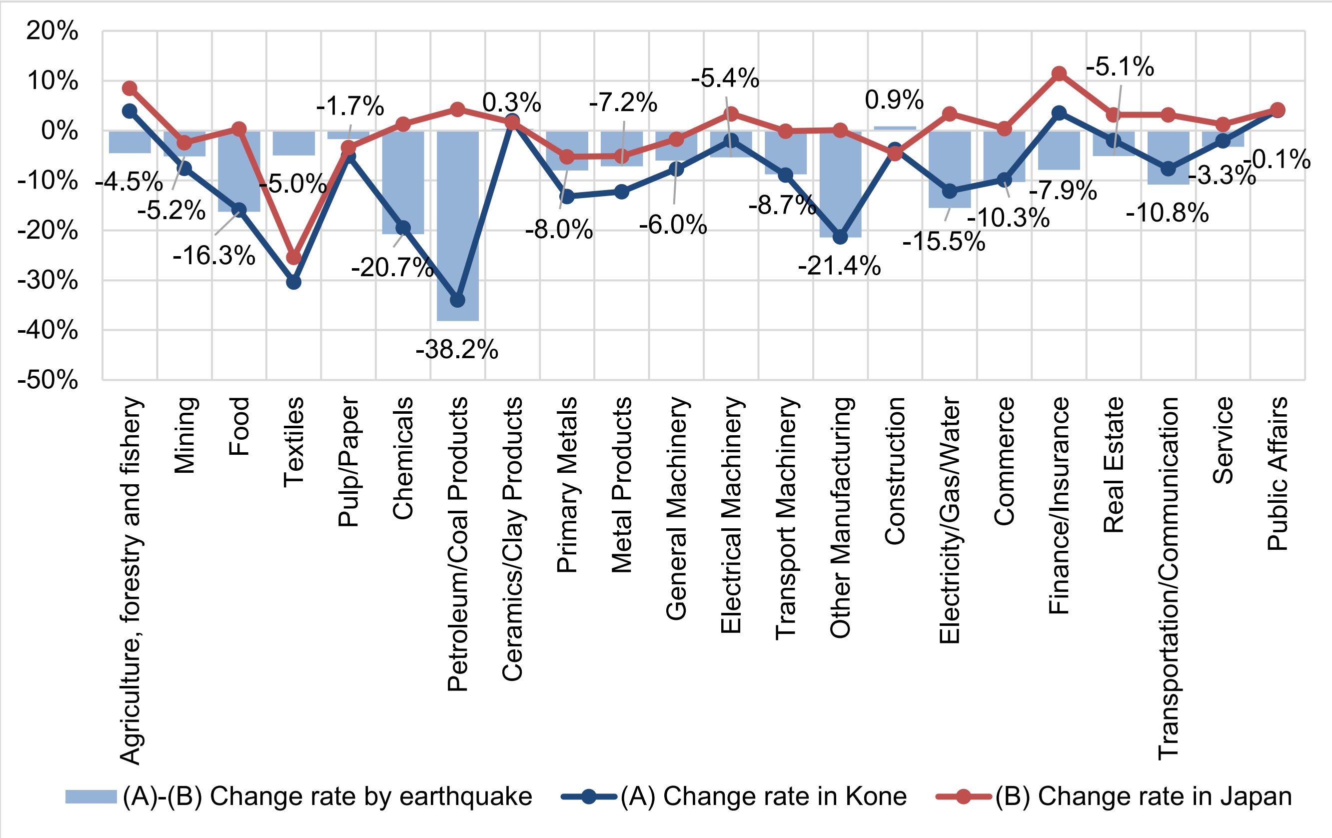

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Figure 4 Percentage changes in the gross regional product by industry (fiscal 1993-94, differences between Kobe City and national figures)

Table 1 summarizes the declines in gross regional product for each industry in Tokyo due to an earthquake computed according to the above assumptions. Tokyo's gross regional product in the first column of numbers in the table is as stated in the Tokyo input–output tables for 2015. The assumed rate of decline in the second column is one based on the experience of the Great Hanshin Earthquake. The third column is the computed amount of decline in Tokyo's gross regional product. Although the rate of decline in basic materials manufacturing industries, such as petroleum and coal products, is high, in terms of monetary value, the decline in service industries such as commerce and information /telecommunications, is higher.

Table 1 Assumed production declines for Tokyo (unit: million yen)

No	Industry name (Integrated major classification)	Production in Tokyo	Assumed reduction rate	Production Reduction
1	Agriculture, forestry and fishery	101,716	−4.5%	−4,622
2	Mining	9,548	−5.2%	−493
3	Food and beverage	1,161,930	−16.3%	−189,235
4	Fiber products	82,896	−5.0%	−4,123
5	Pulp/paper/wood products	285,064	−1.7%	−4,905
6	Chemical products	511,175	−20.7%	−106,055
7	Petroleum and coal products	29,668	−38.2%	−11,333
8	Plastic and rubber products	200,508	−21.4%	−42,956
9	Ceramics, clay and stone products	163,138	0.0%	0
10	Steel	166,037	−8.0%	−13,237
11	Nonferrous metal	74,632	−8.0%	−5,950
12	Metal products	231,285	−7.2%	−16,547
13	General machinery	268,519	−6.0%	−16,101
14	Production machinery	358,661	−6.0%	−21,506
15	Commercial machinery	543,459	−6.0%	−32,587
16	Electronic components	306,774	−5.4%	−16,423
17	Electric machinery	671,171	−5.4%	−35,932
18	Information/communication equipment	564,268	−5.4%	−30,209
19	Transport machinery	1,939,116	−8.7%	−169,640
20	Other manufacturing	1,298,640	−21.4%	−278,212
21	Construction	8,346,040	0.0%	0
22	Electricity/gas/heat supply	1,393,182	−15.5%	−216,147
23	Water supply	652,770	−15.5%	−101,275
24	Waste disposal	459,197	−15.5%	−71,243
25	commerce	24,142,943	−10.3%	−2,480,830
26	Finance/Insurance	11,151,638	−7.9%	−877,757
27	Real estate	14,788,359	−5.1%	−753,522
28	Transportation/mail	7,550,317	−10.8%	−815,329
29	Telecommunications	22,538,640	−10.8%	−2,433,859
30	Public affairs	6,669,910	−0.1%	−4,957
31	Education/Research	7,041,641	−3.3%	−230,537
32	Medical care and welfare	7,279,542	−3.3%	−238,326
33	Private non-profit organization	589,560	−3.3%	−19,302
34	Business service	25,682,677	−3.3%	−840,830
35	Personal service	10,032,750	−3.3%	−328,464
36	Office supplies	289,843	0.0%	0
37	Classification unknown	750,413	0.0%	0
38	Main office	30,707,469	−10.0%	−3,070,747
Total		189,035,096	−7.1%	−13,483,190

Source：created by the authors

This is a technical point, but using Excel Solver, we set the initial value at the final demand per the input–output table and attached non-negative conditions to the optimal solution.

We then assumed three patterns of damage: (A) head office damage, (B) non-head office damage, and (C) head office and non-head office damage (damage to all industries). Based on these assumptions of damage that would reduce production, we ran two simulations: the GDP maximization scenario and the changes in the final demand minimization scenario, both of which are discussed above.

4.2 GDP maximization

Table 2 below shows the computations when the scenario is based on a policy that pursues GDP maximization. These computations find the final demand that maximizes the GDP under a production constraint in which the optimized domestic product is at or below the domestic product under the damage assessments, and the indirect amount of economic damage is considered a reduction of final demand. From these computations, we can infer the following.

(1) Reduction of final demand

The ranking of changes in final demand, from the highest to the lowest, is all industries, head offices only, and non-head offices. Because the reduction in final demand under the damage assessments is greatest for all industries, it is appropriate that the all-industries model also shows the largest reduction in final demand. However, the next largest reduction in final demand after all industries is head offices only, which had the lowest damage assumption. This suggests that damage to head offices in Tokyo plays a major role in reducing final demand in central Tokyo. The change in final demand for all industries came to −3.5%. This means that even if the GDP is maximized under supply constraints in this damage scenario, the indirect economic damage will cause the GDP to decline by 3.5%.

(2) Reduction of final demand by area

What is common to the head offices only, non-head offices, and all-industries models is that while final demand goes down in Tokyo proper, it goes up in the Tokyo suburbs. This means that if Tokyo is damaged by an earthquake, policies to maximize the GDP will cause final demand to decline in central Tokyo and rise in the Tokyo suburbs. The outcome of this scenario is that indirect economic damage is concentrated in central Tokyo.

(3) Reduction of final demand by industrial sector

Among all industries, commerce had the greatest decline in final demand, and it was also the industrial sector with the greatest contribution ratio. Examining the production of commerce for head offices only and non-head offices, it is very interesting that in terms of damage to head offices only, there was a large decline in final demand in the commerce sector, while for damage to non-head offices, such a decline was relatively minor. Services are the sector that comprises the greatest share of final demand in central Tokyo. Among all industries, services were second after commerce in the reduction of final demand. As services have the greatest share of final demand, the amount of a decline will be large, but the percentage change is only −12%. The reduction in final demand is about 22 trillion yen for all industries, but in terms of contribution ratio, we can see that commerce and services are the major contributors to the decline. In summary, damage to Tokyo causes a reduction of final demand in central Tokyo and an increase in final demand in the Tokyo suburbs. In addition, we see that the reduction in final demand in central Tokyo is caused by the commerce and services industries.

Table 2 Computations for GDP maximization

		FD before earthquake (bill. Yen)	Change in Final demand (billion yen)			Change in Final demand (%)			Contribution (%)		
			Main office only	Except main office	All industries	Main office only	Except main office	All industries	Main office only	Except main office	All industries
In Tokyo	Agriculture/Mining	52	29	−2	9	56.4	−3.9	18.1	0.2	0.0	0.0
	Manufacturing	4,770	−1,073	−3,483	−3,092	−22.5	−73.0	−64.8	−5.6	−33.3	−14.3
	Construction	7,730	44	−1,181	72	0.6	−15.3	0.9	0.2	−11.3	0.3
	Electricity/gas	850	476	−439	−51	56.0	−51.6	−6.0	2.5	−4.2	−0.2
	Commerce	15,659	−15,659	−2,258	−15,659	−100.0	−14.4	−100.0	−82.2	−21.6	−72.2
	Service	61,290	−7,022	−6,965	−7,383	−11.5	−11.4	−12.0	−36.9	−66.6	−34.0
	Main office	0	0	1,070	0	-	-	-	0.0	10.2	0.0
Outside Tokyo	Agriculture/Mining	3,610	396	65	225	11.0	1.8	6.2	2.1	0.6	1.0
	Manufacturing	134,025	600	1,005	891	0.4	0.8	0.7	3.1	9.6	4.1
	Construction	49,407	4	5	6	0.0	0.0	0.0	0.0	0.0	0.0
	Electricity and gas	8,911	360	203	333	4.0	2.3	3.7	1.9	1.9	1.5
	Commerce	47,281	620	357	479	1.3	0.8	1.0	3.3	3.4	2.2
	Service	283,901	422	529	724	0.1	0.2	0.3	2.2	5.1	3.3
	Main office	0	1,751	636	1,760	-	-	-	9.2	6.1	8.1
A. Tokyo total		90,351	−23,204	−13,257	−26,104	−25.7	−14.7	−28.9	−121.8	−126.8	−120.4
B. Outside Tokyo total		527,135	4,155	2,800	4,418	0.8	0.5	0.8	21.8	26.8	20.4
C. Japan total		617,486	−19,050	−10,457	−21,686	−3.1	−1.7	−3.5	−100.0	−100.0	−100.0

(Note) Contribution ratios are calculated so that the total is −100.
Source: created by the authors

4.3 Minimization of changes in final demand

Table 3 shows the computations for the scenario focused on minimizing changes in final demand. This scenario assumes that the policy is to minimize the total change in the GDP after the earthquake when compared with the GDP before the earthquake. In other words, we assume that the policy is to minimize the shock that the earthquake exerts on the GDP. From these computations, we can infer the following.

(1) Reduction of final demand

Ranking the changes in final demand from highest to lowest, we get all industries, head offices only, and non-head offices. However, the difference between head offices only and all industries is minimal. This suggests that damage to head offices in Tokyo would have a major impact on reducing production nationwide. This outcome is similar to the computations from the GDP maximization scenario above.

(2) Decrease in production value by region

What is common to head offices only, non-head offices, and all industries is that final demand declines in Tokyo proper as well as in the Tokyo suburbs. This is very different from the GDP maximization scenario, in which the indirect economic damage from the earthquake was limited to central Tokyo. For all industries nationwide, the decline in final demand was about 47 trillion yen. When compared with the 22 billion yen decline calculated in the GDP maximization scenario, this is a very large amount of indirect economic damage. Furthermore, the reduction in final demand in central Tokyo is 16 trillion yen in the “minimizing the total change in final demand” scenario and 26 billion yen in the “GDP maximization” scenario. In other words, even though we can also say that on a nationwide basis, the “minimizing total change in final demand” scenario leads to a larger reduction in final demand than the “GDP maximization” scenario, the impact on central Tokyo is limited.

(3) Decrease in output by industrial sector

Examining the contribution ratio for all industries, we see that manufacturing and services have a major impact on the decline in final demand. At the same time, the impact on commerce, which had the greatest indirect economic damage in the GDP maximization scenario, is very limited. In addition, as stated earlier, final demand went down in all industrial sectors in both Tokyo proper and suburban Tokyo. In terms of the contribution ratio, it is notable that manufacturing and services are major contributors to the decline in final demand.

In summary, under this policy goal, the outcome is that damage to central Tokyo leads to a reduction in final demand in both central Tokyo and the Tokyo suburbs. In addition, despite the damage in central Tokyo, the reduction in final demand in the Tokyo suburbs is considerable when compared with that in central Tokyo.

Table 3 Computations for minimization of changes in final demand

		FD before earth-quake (bill. Yen)	Change in Final demand (billion yen)			Change in Final demand (%)			Contribution (%)		
			Main office only	Except main office	All industries	Main office only	Except main office	All industries	Main office only	Except main office	All industries
In Tokyo	Agriculture/Mining	52	−6	−13	−10	−10.6	−25.2	−18.4	0.0	−0.1	0.0
	Manufacturing	4,770	−604	−1,177	−801	−12.7	−24.7	−16.8	−1.3	−4.5	−1.7
	Construction	7,730	−518	−1,007	−949	−6.7	−13.0	−12.3	−1.1	−3.9	−2.0
	Electricity/gas	850	−111	−362	−296	−13.1	−42.6	−34.8	−0.2	−1.4	−0.6
	Commerce	15,659	−3,257	−2,019	−2,953	−20.8	−12.9	−18.9	−7.0	−7.8	−6.3
	Service	61,290	−8,286	−8,536	−11,118	−13.5	−13.9	−18.1	−17.9	−32.8	−23.7
	Main office	0	0	0	0	-	-	-	0.0	0.0	0.0
Outside Tokyo	Agriculture/Mining	3,610	−376	−135	−328	−10.4	−3.8	−9.1	−0.8	−0.5	−0.7
	Manufacturing	134,025	−11,063	−8,384	−11,061	−8.3	−6.3	−8.3	−23.8	−32.2	−23.6
	Construction	49,407	−1,921	−916	−1,860	−3.9	−1.9	−3.8	−4.1	−3.5	−4.0
	Electricity and gas	8,911	−894	−422	−906	−10.0	−4.7	−10.2	−1.9	−1.6	−1.9
	Commerce	47,281	−4,776	−519	−3,894	−10.1	−1.1	−8.2	−10.3	−2.0	−8.3
	Service	283,901	−14,575	−2,534	−12,638	−5.1	−0.9	−4.5	−31.4	−9.7	−27.0
	Main office	0	0	0	0	-	-	-	0.0	0.0	0.0
A. Tokyo total		90,351	−12,782	−13,113	−16,126	−14.1	−14.5	−17.8	−27.6	−50.4	−34.4
B. Outside Tokyo total		527,135	−33,604	−12,912	−30,687	−6.4	−2.4	−5.8	−72.4	−49.6	−65.6
C. Japan total		617,486	−46,386	−26,024	−46,813	−7.5	−4.2	−7.6	−100.0	−100.0	−100.0

(Note) Contribution ratios are calculated so that the total is −100.
Source: created by the authors

5. Conclusion

The analysis in this paper has focused on resource allocation that adjusts the volume of demand as a means to deal with supply constraints caused by an earthquake. This analytical methodology differs from traditional input–output analysis in that, the computations consider supply constraints (production constraints) to be an exogenous variable and the final demand supplied to be an endogenous variable. In addition, we assume policy objectives (objective functions) that will deal with the supply constraints caused by the earthquake and run a mathematical optimization model to find the endogenous variable of final demand.

We also use this mathematical optimization model to calculate earthquake damage (the amount of indirect economic damage) by finding the difference between pre- and post-earthquake final demand. Another major characteristic is that while we made the supply constraint equivalent to the assumed amount of direct damage, we also calculated the amount of indirect economic damage based on policy decisions for dealing with the direct damage.

This paper assumed two potential policy objectives: GDP maximization and minimization of changes in final demand (minimization of the total change in GDP before and after the earthquake). These two policy decisions led to opposing outcomes regarding the indirect economic damage from the earthquake.

For the policy goal of maximizing the GDP, the impact on final demand was limited to central Tokyo. However, for the policy goal of minimizing the change in final demand, the impact of a reduction in final demand extended to both central Tokyo and suburban Tokyo. In other words, the impact was nationwide.

If we are to draw policy implications from these results, we could say that when resource allocation of final demand aims to maximize the GDP, the damage can be limited mainly to central Tokyo. However, we could also say that when resource allocation of final demand aims to minimize the total change in final demand before and after an earthquake (or aims to minimize the change in the GDP before and after an earthquake), the damage will cover both central and suburban Tokyo. We can come up with many policies for dealing with earthquakes. Using the analytical methodology in this paper, it is possible to clarify the scale of the impact of indirect economic damage by assuming that several potential policy decisions are made in a supply-constraint situation and using them to optimize the outcome.

Finally, let us note some remaining issues. The first is that we did not consider any changes in the input coefficient. In our analysis, the input coefficient was constant before and after the earthquake. It is typically thought that the input production structure will change before and after an earthquake. Second is the treatment of imports. In this paper, the final demand is entirely domestic, and imports are not considered. Incorporating imports into the final demand or changing the import coefficient would probably make our simulation more realistic.

In the future, we would like to consider these issues while conducting an analysis that employs several policy options, including the maximization of household utility and a model that holds down price increases.

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Remark

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