Modeling spatial economic impacts of an earthquake: input-output approaches

Yasuhide Okuyama

The author

Yasuhide Okuyama is a Research Associate at the Regional Research Institute, West Virginia University, Morgantown, Virginia, USA.

Keywords

Modelling, Earthquakes, Input/output analysis, Economic measurement

Abstract

Economic modeling issues for measuring damages and losses from disasters and their impacts are complex. The questions surrounding the potential economic effects of a disaster have been studied and discussed in various aspects. Input-output analysis has been employed in many studies to measure and evaluate the economic impacts of disasters, mainly because of the ability to reflect the structure of regional economy in great detail. Whereas they provide useful information regarding the economic impacts and consequences and about the resource allocation strategies to minimize the losses and impacts, many of these studies have failed to investigate the dynamic nature of impact path over space and time, due to the difficulties to obtain such data and also to the static nature of input-output framework. In order to analyze the spatial impacts of a disaster, Miyazawa's extension to the conventional input-output framework is employed and is applied for the case of the Great Hanshin Earthquake.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0965-3562.htm

Disaster Prevention and Management
Volume 13 · Number 4 · 2004 · pp. 297-306

DOI 10.1108/09653560410556519

1. Introduction

The damages and losses by disasters, such as earthquakes, floods, tornadoes, and other major natural disasters, or man-made disasters, have significant and intense impacts on a region's economy. In addition, the impacts from the damages will sustain over time, and will spread serious economic effects to other regions. Furthermore, the impacts of disasters are very complex, including not only the negative effects from damages and losses, but also the positive economic effects from the recovery and reconstruction activities. Most economic models and techniques have difficulty to confront these significant changes in a relatively short time period, since they assume incremental, or predictable, changes in a system over time. In addition, the unexpected nature of these events, especially in the case of earthquakes, creates a further complication of measuring the indirect impacts.

While the economic modeling issues for measuring such disruptions and the impacts are more complex (for an excellent summary, see West and Lenze, 1994), the questions of the potential economic effects of a disaster have been studies and discussed in various aspects (for example, Cochrane, 1974; National Science of Academy, 1978; Chang, 1983; Ellson *et al.*, 1984; and Guimaraes *et al.*, 1993, among others). Input-output analysis has been employed in many studies to measure and evaluate the economic impacts of disasters, mainly because of the ability to reflect the structure of regional economy in great detail (e.g. Cochrane, 1974, 1995, 1999; Wilson, 1982; Kawashima *et al.*, 1991; Boisverst, 1992; Gordon and Richardson, 1996; Cole, 1997; Rose *et al.*, 1997; Rose and Benavides, 1998; Okuyama *et al.*, 1999a). Whereas they provide useful information regarding the economic impacts and consequences and about the resource allocation strategies to minimize the losses and impacts, many of these studies have failed to investigate the dynamic nature of impact path over space and time, due to the difficulties to obtain such data and also to the static nature of input-output framework.

This is an inherent problem for impact analysis of disasters; as West and Lenze (1994) pointed out,

---

This research was supported by the National Science Foundation, Award No. CMS-0099724. The author is grateful to the encouragements and comments from Eliahu Romanoff and Stephen Levine, and to the comments given at the workshop on "In search of a common methodology on damage estimation", organized by the European Commission and Universiteit Twente, in Delft, The Netherlands, May 23 and 24, 2003.

the sophisticated regional impact models requiring precise numerical input have to be reconciled with imperfect measurements of the damages and losses. Moreover, measuring the economic effects of a disaster poses a great challenge for modeling the event *per se* and its consequences – damages and losses occur across various geographical areas and in a relatively short period of time, while the economic effects spread over a region (and, oftentimes, to other regions, too) and, in some cases, may last for a relatively long period of time. In order to capture the spatial and time dimensions of disaster impacts, this paper employs two methods: Miyazawa's extended input-output framework (Miyazawa, 1976) for estimating the spatial impacts of an earthquake and its recovery process; and the sequential interindustry model (SIM), introduced by Romanoff and Levine (1977) for example, for investigating the dynamic process of the impact paths of a disaster while maintaining the simplicity of input-output framework. In the next section, the Miyazawa's extended input-output framework is presented and applied to the Great Hanshin Earthquake (1995, Kobe, Japan) to estimate the interregional impacts of the earthquake. In section 3, the analytical framework of SIM is presented and discussed. In section 4, a hypothetical application using the SIM framework is presented and used for the sensitivity analysis of uncertainty. Finally, section 5 summarizes and concludes this paper, and addresses some future research needs for linking economic and engineering models.

2. Spatial impacts of an earthquake: Miyazawa's framework and the Great Hanshin Earthquake

In order to analyze the spatial impacts of a disaster, the Miyazawa's extension to the conventional input-output framework is employed and is applied for the case of the Great Hanshin Earthquake.

2.1 Miyazawa's extended framework

Miyazawa's concept of the interrelational income multiplier was designed to analyze the structure of income distribution by endogenizing consumption demands in the standard Leontief model. Especially in an interregional context, this inclusion of the income formation process has clear advantages for linking the location of production and the location of consumption. These ideas were also incorporated in the familiar social accounting systems developed by Stone (1961), Pyatte and Roe (1977), and in the parallel developments of demographic-economic modeling associated with Batey and Madden (1983). In some sense, Miyazawa's system may be considered the most parsimonious in terms of the way it extends the familiar input-output formulation. Miyazawa considered the following system:

$$\begin{pmatrix} \mathbf{x} \\ \mathbf{y} \end{pmatrix} = \left(\begin{array}{c|c} \mathbf{A} & \mathbf{C} \\ \hline \mathbf{V} & \mathbf{0} \end{array}\right) \begin{pmatrix} \mathbf{x} \\ \mathbf{y} \end{pmatrix} + \begin{pmatrix} \mathbf{f} \\ \mathbf{g} \end{pmatrix}, \tag{1}$$

where **x** is a vector of output, **y** is a vector of total income for some *r*-fold division of income groups, **A** is a block matrix of direct input coefficients, **V** is a matrix of value-added ratios for *r*-fold income groups, **C** is a corresponding matrix of consumption coefficients, **f** is a vector of final demands except households consumption, and **g** is a vector of exogenous income for *r*-fold income groups. Solving this system yields:

$$\begin{pmatrix} \mathbf{x} \\ \mathbf{y} \end{pmatrix} = \left(\begin{array}{c|c} \mathbf{B(I + CKVB)} & \mathbf{BCK} \\ \hline \mathbf{KVB} & \mathbf{K} \end{array}\right) \begin{pmatrix} \mathbf{f} \\ \mathbf{g} \end{pmatrix}, \tag{2}$$

where $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix, **BC** is a matrix of production induced by endogenous consumption, **VB** is a matrix of endogenous income earned from production, $\mathbf{L} = \mathbf{VBC}$ is a matrix of expenditures from endogenous income, and $\mathbf{K} = (\mathbf{I} - \mathbf{L})^{-1}$ is a matrix of the Miyazawa interrelational income multipliers.

The advantages of this Miyazawa's formulation are that: this is the most parsimonious way to model the structure of product generation and income distribution, in terms of the data requirements; and it has a clear advantage for linking the location of production and the location of consumption. Extending a conventional interregional input-output table to this Miyazawa's formulation, spatial impacts of the Great Hanshin Earthquake is evaluated in the next sub-section.

2.2 The Great Hanshin Earthquake: empirical application

At 5.46 am, on January 17, 1995, the worst disaster in post-War Japan struck the second largest region of Japan – the Kinki region. The city of Kobe and surrounding municipalities experienced massive destruction of houses, buildings, roads, rails, and infrastructure. The direct damages from the Great Hanshin Earthquake were estimated at about 10 trillion yen (100 billion dollars) according to the Hyogo prefecture government, equivalent to about 2.1 percent of Japan's GDP (gross domestic product) and 11 percent of Kinki's GRP (gross regional product). These direct damages were concentrated in the destruction of buildings (including houses and production facilities), of transportation facilities (port, roads, and rails), and utilities (water, sewage, gas, and electricity). Although the damaged geographical area is only 4 percent of Kinki, it includes 15 percent of Kinki's population. These direct damages, inevitably, may have significant effects not only on the Kinki region but also on other regions. The loss of capital stocks, however, was 0.8 percent of Japan's total, while it was 10.5 percent in the Great Kanto Earthquake in 1923 (Yomiuri Newspaper, June 20, 1995).

Immediately after the event, various studies assessing the direct and indirect damages from the event were carried out by many institutions. The increase of final demand, especially in construction sector, for the recovery and reconstruction activities, furthermore, has also been estimated in various ways (see the summary and critique in Miyao, 1995). Based on these estimates of the damages and losses, in this study, the spatial effects of the Great Hanshin earthquake are evaluated using a two-region (Kinki and rest of Japan) system with the Miyazawa's extended input-output framework derived from the 1985 interregional input-output table published by the Ministry of International Trade and Industry (MITI, 1990) of Japan (for the details of the assumptions and settings, see Okuyama *et al.*, 1999a). The impacts are calculated for two cases over three years: without reconstruction activities for estimating only the negative impacts of the earthquake; and with reconstruction activities for analyzing both the negative impacts of the earthquake and the positive impacts of reconstruction demand injection.

Without the reconstruction demand in the construction sector, the negative impacts on income formation are shown in both regions (see Table I). The striking result is that the decrease of income formation in Kinki originating in the rest of Japan has the largest negative impacts. Since the size of the economy in the rest of Japan is substantially larger than that in Kinki and about 83 percent of income in Japan is generated from the rest of Japan, this seems a reasonable result. Adding the reconstruction demand to the construction sector in Kinki, the demand injection creates positive impacts on income formation in Kinki and the imports from the rest of Japan to Kinki, while the overall impact (total impact) is still a negative value. Thus, the reconstruction activities in Kinki have considerable impacts on the income formation in Kinki and in the rest of Japan.

The effects on the changes in gross output in both regions are derived and these are shown in Table II. The general tendencies of the results are similar to the impacts on income formation. Without reconstruction demand after the event, Kinki's output decreases more substantially than the rest of Japan's. With the injection of construction demand, the overall size of the results is similar to those generated in the income formation analysis. However, the case with reconstruction demand indicates positive impacts in Kinki and in total, while the rest of Japan has negative impacts in both cases. Moreover, the differences in outputs between those in Kinki and in the rest of Japan tend to increase in the gross output case, whereas they decrease in the income formation case. This may indicate that the demand injection generated by reconstruction in Kinki has different impacts in Kinki from those in the rest of Japan.

Note that the demand injection for the reconstruction activities in Kinki is just added to the Kinki's final demand, without allocated from the rest of Japan, which in turn decreases the final demand (government expenditures) in the rest of Japan. In reality, the public (or private) funds should be re-allocated from elsewhere to carry out the reconstruction activities in Kinki, resulting the cancellation or postponement of current or future projects. This will create another complex problem of how to reallocate the funds from other regions (or programs) for the reconstruction. The impacts of this interregional (and/or inter-program) allocation of funds may create the further negative

Table I Changes of direct and indirect income-formation

	Region of demand origin		
	Kinki	Rest of Japan	Total (1995 million yen)
Region of income receipt			
Kinki	−936,190	−1,168,787	−2,104,977
	1,108,274	−1,168,787	−60,513
Rest of Japan	−738,664	−937,145	−1,675,809
	814,125	−937,145	−123,020
Total	−1,674,853	−2,105,932	−3,780,785
	1,922,400	−2,105,932	−183,532

Note: Upper row for without reconstruction demand; lower row for with reconstruction demand

Table II Changes of gross output

	Region of demand origin		
	Kinki	Rest of Japan	Total (1995 million yen)
Region of production			
Kinki	−3,223,619	−4,075,031	−7,298,650
	4,619,270	−4,075,031	544,239
Rest of Japan	−3,109,290	−3,938,725	−7,048,016
	3,463,595	−3,938,725	−475,130
Total	−6,332,909	−8,013,757	−14,346,666
	8,082,865	−8,013,757	69,108

Note: upper row for without reconstruction demand; lower row for with reconstruction demand impacts in the Rest of Japan, and may influence the long-term economic recovery in Kinki and the rest of Japan. This type of study will be required for more comprehensive analysis of reconstruction and recovery process, while it is beyond the scope of the study.

3. Temporal impacts of a disaster: SIM

Early interest in the dynamics of interindustry production within the framework of input-output analysis can be seen in Goodwin (1947) and Leontief (1951), expanded by Dorfman *et al.* (1958), Kuenne (1963), further advanced by Morishima (1964), and extended to the integration with linear programming, and/or to computable general equilibrium (CGE) modeling. As another line of the effort, a dynamic version of input-output model was first introduced by Leontief (1953) and was modified in his 1970 study (Leontief, 1970), aiming to analyze and determine the structural and the technological changes of an economy by including an intertemporal mechanism of capital accumulation.

Based on a different approach to introduce a dynamic structure in the static input-output framework, a group of lagged input-output models with distributed activities were also proposed (for example, ten Raa, 1986; Cole, 1988, 1989). As a similar approach but with more emphasis on production chronology, Romanoff and Levine introduced the SIM in order to investigate the impacts on production process and to analyze the temporal distribution of the economic impacts. In the following part, the SIM framework is presented and discussed.

3.1 SIMs

Levine and Romanoff (1989), Romanoff (1984), and Romanoff and Levine (1977, 1981, 1986, 1990a, b, 1991, 1993) introduced the SIM in response to the need to analyze interindustry production in a dynamic economic environment, such as large construction projects where the effects on production and employment are transitory. Assuming that time is divided into discrete intervals of equal duration, SIM enhances the static input-output model to the dynamic one by supplementing the structure of production with a production chronology. In SIM, production is not simultaneous as in the static input-output model, but rather occurs sequentially over a period of time. The interval of an industry production process is divided into two components: the production interval and the shipment interval with inputs and product inventories. In order to create the dynamic process, a distinction is made among three events in a production process: demand stimulus occurs when goods are ordered; yield or supply happens when goods are delivered; and production yield occurs when goods are produced. Thus, demand is not restricted to final demand but includes intermediate demand along the production sequences, as in the standard input-output framework. Final demand stimulus is the ultimate system input, while final yield or final supply is the net system output.

Determining the dynamics of interindustry production, two simplified production modes are proposed in SIM: anticipatory production mode and responsive production mode. The anticipatory production mode is typical in agriculture and many manufacturing industries, in which the production is made in anticipation of future orders. In this mode, producers' specifications result in ready-made standards products and in holding product inventory. On the other hand, responsive production takes place after the receipt of orders, responding to customers' specification by producing to meet the unique requirements, while product inventory is unlikely. This production mode is typical of some manufacturing, most of construction and ordnance industries, and most of services industries[1] (Romanoff and Levine, 1981, 1986).

In the time-varying SIM, time indices, which pertain to production technique in use and to temporal events or intervals, are defined as follows (Romanoff and Levine, 1990a, b):

t = time interval of input application;
σ = time interval of output or production completion;
h_{ij} = application period of an input from industry i used by industry j, referenced from the initial application interval t, to product completion σ;
h_j = production period of industry j, equivalent to the longest application period of h_{ij};
$t-\sigma$ = input duration, indicating the period from an input application interval t to the time of output completion, σ, equal or longer than h_j; and
ϕ_{ij} = transportation delay associated with the shipment from industry i to industry j, representing the components of the transportation delay matrix, $\mathbf{\Phi}$.

3.2 Anticipatory production mode

Assuming just-in-time production on the input side (no input inventory), the input price from industry i to j is given by $p_i(t-\phi_{ij})$, since the input price is determined at the time that it leaves supplying industry i. The quantity of input from i

to j is defined as $q_{ij}(\mu_{t,ij}; t, \sigma)$, processed by technology μ at time t in industry j using input from i in order to complete the product at σ. The value of transaction form i to j is:

$$x_{ij}(\mu_{t,ij}; t, t-\phi_{ij}, \sigma) = p_i(t-\phi_{ij}) \cdot q_{ij}(\mu_{t,ij}; t, \sigma). \tag{3}$$

The total output of industry j, x_j, completed at σ is priced at the time of product completion for anticipatory production mode is:

$$x_j(\sigma, \sigma) = p_j(\sigma) \cdot q_j(\sigma), \tag{4}$$

where $q_j(\sigma)$ is the quantity of output produced by j at σ. Using equations (3) and (4), the time-phased technical coefficients can be derived as follows:

$$a_{ij}(\mu_{t,ij}; t, t-\phi_{ij}, \sigma, \sigma) = \frac{x_{ij}(\mu_{t,ij}; t, t-\phi_{ij}, \sigma)}{x_j(\sigma, \sigma)}. \tag{5}$$

Hence, total intermediate output produced by industry i becomes:

$$w_i(t, t) = \sum_{\sigma} \sum_{j} \sum_{\mu} a_{ij}(\mu_{t,ij}; t, t-\phi_{ij}, \sigma, \sigma) \cdot x_j(\sigma, \sigma), \tag{6}$$

which is a generalized convolution indicating the dynamics of intermediate production. Then, the accounting identity of industry i will become in the matrix form as follows:

$$\mathbf{x}(t, t) = \sum_{\sigma} \mathbf{A}(\mathbf{M}; t, t-\phi_0, \sigma, \sigma) \cdot \mathbf{x}(\sigma, \sigma) + \mathbf{u}(t, t) + \mathbf{y}(t, t), \tag{7}$$

where $\mathbf{M}$ is the technology matrix, and ϕ_0 indicates the appropriate elements of the transportation delay matrix, $\mathbf{\Phi}$. This formulation is a fully specified version of their Core SIM presented in Romanoff (1984) and Romanoff and Levine (1981), with an exception of inventory. Model (7) becomes in the reduced form as follows:

$$\mathbf{x_t} = \mathbf{Ax_{\boldsymbol{\sigma}}} + \mathbf{u_t} + \mathbf{y_t}. \tag{8}$$

The major assumption in terms of inventory is that, unlike final demand that is exogenous of the system, inventory is an endogenous function based on inventory policies of anticipatory producer. However, Romanoff and Levine (1990a, b, 1991) did not fully specify the inventory management function within SIM.

3.3 Responsive production mode

While producers' price, $p_i(t-\phi_{ij})$, may be better suited for anticipatory producers, they may also be applicable to responsive producers (Romanoff and Levine, 1990a, b). Therefore, equation (4) holds also for responsive production mode. What make responsive production mode different from anticipatory mode is in the time of output pricing, i.e. for responsive producers, the price of output is determined when an order is issued. Hence, this ordering lead time, ε_j, is set ahead of beginning of the production interval, h_j from the production completion at σ. Then, the total output of industry j becomes:

$$x_j(\sigma, \sigma-h_j-\varepsilon_j) = p_j(\sigma-h_j-\varepsilon_j) q_j(\sigma). \tag{9}$$

Consequently:

$$a_{ij}(\mu_{t,ij}; t, t-\phi_{ij}, \sigma, \sigma-h_j-\varepsilon_j) = \frac{x_{ij}(\mu_{t,ij}; t, t-\phi_{ij}, \sigma)}{x_j(\sigma, \sigma-h_j-\varepsilon_j)}. \tag{10}$$

The total output of responsive production mode in the matrix form is:

$$\mathbf{x}(t, t-h_j-\varepsilon_j) = \sum_{\sigma} \mathbf{A}(\mathbf{M}; t, t-\phi_0, \sigma, \sigma-h_j-\varepsilon_j) \cdot \mathbf{x}(\sigma, \sigma-h_j-\varepsilon_j) + \mathbf{y}(t, t-h_j-\varepsilon_j). \tag{11}$$

Note that responsive production mode is, of its nature, without production inventory[2]. This formulation can also be compared to a simpler version in Core SIM, and corresponding responsive production mode in Core SIM can be re-written as the following reduced form:

$$\mathbf{x_t} = \mathbf{Ax_{\sigma-h-\varepsilon}} + \mathbf{y_t}. \tag{12}$$

3.4 Combined anticipatory-responsive production model

Since the input-output model is a multi-sector framework, it is natural to assume that anticipatory production and responsive production industries are coupled with each other in the model. The anticipatory production mode in equation (7) and the responsive production mode in equation (11) are distinguished in a way that the anticipatory mode does not require ordering lead time ($h_j + \varepsilon_j = 0$), whereas the responsive mode does not include the production inventory. Therefore, the combined anticipatory-responsive model encompasses both properties as follows:

$$\mathbf{x}(t, t-h_j-\varepsilon_j) = \sum_{\sigma} \mathbf{A}(\mathbf{M}; t, t-\phi_0, \sigma, \sigma-h_j-\varepsilon_j) \cdot \mathbf{x}(\sigma, \sigma-h_j-\varepsilon_j) + \mathbf{u}(t, t) + \mathbf{y}(t, t-h_j-\varepsilon_j). \tag{13}$$

While this version of SIM combines the anticipatory mode and responsive production mode industries, each industry is classified into one of the production modes. Again, the model

(13) can be re-written for corresponding to the Core SIM version as follows:

$$\mathbf{x_t} = \mathbf{A}\mathbf{x}_{\sigma-\mathbf{h}-\varepsilon} + \mathbf{u_t} + \mathbf{y_t}. \tag{14}$$

Based on this combined model in equation (14), the Leontief inverse can be obtained as follows:

$$\mathbf{x_t} = \boldsymbol{\beta}\left[\mathbf{A}(.), \mathbf{u_t}, \mathbf{y_t}\right], \tag{15}$$

where $\boldsymbol{\beta}[.]$ is a vector function, or calculation rule, representing a general extension of the Leontief inverse. The specification of this function depends on the inventory function (Romanoff and Levine, 1990a, b). In the static version, with $\mathbf{u_t} = 0$, model (15) becomes $\mathbf{x} = \boldsymbol{\beta}\left[\mathbf{A}, \mathbf{y}\right] = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, the standard static Leontief inverse.

Table III Sector and production mode assignment

No.	Sector	Mode assignment
1	Agriculture, forestry, and fisheries	Anticipatory
2	Mining	Anticipatory
3	Construction	Responsive
4	Food and kindred products	Just-in-time
5	Chemicals and allied products	Just-in-time
6	Primary metals industries	Anticipatory
7	Fabricated metal products	Anticipatory
8	Industrial machinery and equipment	Anticipatory
9	Electronic and electric equipment	Anticipatory
10	Transportation equipment	Anticipatory
11	Other non-durable manufacturing	Just-in-time
12	Other durable manufacturing	Anticipatory
13	TCU, services, and government enterprises	Just-in-time
14	Electric, gas, and sanitary services	Just-in-time

4. SIM and lifeline damage: a hypothetical case in Chicago

As an illustrative example, a hypothetical lifeline (power line) disruption is imposed on the Chicago region economy, and the SIM framework is applied to evaluate the temporal distribution of the economic impacts.

4.1 Case of lifeline disruptions

Unlike the catastrophic damages and losses of the Great Hanshin Earthquake, most disasters have relatively less significant direct damages. Even less tragic, the damages to lifelines, such as electricity, water, etc., may have extensive indirect impacts to the economy. In order to display how a lifeline disruption, which may last only a short period of time, causes the indirect impacts over time, a hypothetical case is set up and is applied to the Chicago region economy. The 1992 Chicago region input-output table is extracted from the Chicago region econometric input-output model (CREIM; see the details in Israilevich *et al.*, 1997) and is aggregated to 14 sectors (see Table III). Each sector is assigned to one of the three production modes: anticipatory, responsive, or just-in-time.

The annual input-output table is, then, transformed to a quarterly system (one quarter is three months; four quarters in one year) to implement the SIM framework. The combined anticipatory-responsive SIM model (14) is modified to fit with the sector assignment and the assumptions in the following manner. First, the model is simplified into the core SIM version in Romanoff and Levine (1981), using a simpler specification in time phase and production process. Secondly, the inventory function, $\mathbf{u_t}$, is not included in the model, since the lack of empirical data for the inventory strategy of each sector. Third, the sectors are assigned to three different production modes – anticipatory, responsive, and just-in-time modes – with the specified time lags. The applicable model can be written as follows:

$$\mathbf{x_t} = \mathbf{A_a}\mathbf{x}_{\mathbf{t+1}} + \mathbf{A_r}\mathbf{x}_{\mathbf{t-1}} + \mathbf{A_j}\mathbf{x_t} + \mathbf{y_t}, \tag{16}$$

where $\mathbf{A_a}$ is the direct input coefficient matrix for the anticipatory mode sectors with one quarter anticipation; $\mathbf{A_r}$ is for the responsive mode sectors with one quarter response period; and $\mathbf{A_j}$ is for the just-in-time mode sectors. The solution of this model becomes:

$$\mathbf{x_t} = \sum_{k=1}^{\infty} \mathbf{A_a^k}\mathbf{y}_{\mathbf{t+k}} + \sum_{k=1}^{\infty} \mathbf{A_r^k}\mathbf{y}_{\mathbf{t-k}} + \sum_{k=0}^{\infty} \mathbf{A_j^k}\mathbf{y_t} + \sum_{k=-\infty}^{\infty} \mathbf{G_k}\left(\mathbf{A_a}, \mathbf{A_r}, \mathbf{A_j}\right)\mathbf{y}_{\mathbf{t-k}}, \tag{17}$$

where $\mathbf{G_k}\left(\mathbf{A_a}, \mathbf{A_r}, \mathbf{A_j}\right)$ is a matrix function whose *ij* element contains the sum of synergetic path gains among different production modes from industry *i* to *j* with a total delay of *k*.

A hypothetical disaster (for example an earthquake) is assumed to occur at the beginning of the first quarter of the simulation, and it damages the lifeline. The lifeline disruption is set as a production capacity constraint: one unit decrease in sector 14's output level. As the most empirical cases, the lifeline damage is recovered and restored within the first quarter. This short duration of capacity constraint in the lifeline sector causes the input constraint to the other sectors and creates the production constraints in their production. These production constraints in the other sectors are calculated using the input requirement of lifeline for each sector. Then, these decreased output levels are converted to the final demand change in each sector, by dividing the changes in gross output by the diagonal term of the Leontief inverse (Miller and Blair, 1985). Since the direct damages are only on Lifeline sector, it is assumed that there are no significant demand injections for the reconstruction. Hence, all other quarters do not have any changes in final demand.

4.2 Analysis of SIM simulation

The impacts of the hypothetical lifeline disruption are calculated based on the case set up above. Figure 1 indicates the impacts on gross output in each quarter. Quarter 1, when the lifeline disruption occurred, has the largest negative impact. While there is no lifeline disruption during quarter 2 and afterwards, the indirect effects sustained until quarter 4. Since the initial damage is set as a unit decrease, the calculated impact can be considered as the temporal multiplier of the impact. These temporal impacts are disaggregated to each production mode in Figure 2. Since lifeline sector (sector 14) belongs to the just-in-time mode, JIT has the largest total impacts in quarter 1, and has continuous impacts during quarters 2 and 3. The total impact on the anticipatory mode is relatively large in quarter 1, and becomes very small in quarter 2, and disappears in quarter 3. The responsive mode sector (construction) has the largest total impacts in quarter 2 and relatively small impacts during quarters 1 and 3, and has sustained impacts until quarter 4. These differences among the modes reflect the difference in production chronology among the modes.

The production chronology set in the SIM framework leads to position the first round impacts from the final demand decrease caused by lifeline disruption at quarter 1. The just-in-time mode's first round impacts are generated at quarter 1 with the largest negative impact at quarter one and decreasing trend afterwards in Figure 2, since there is no production time lag for this mode. For the responsive mode, the first round impact is generated at quarter 2, since their production responds to the final demand at one quarter prior. Thus, the responsive mode has their largest negative impacts in quarter 2, and much smaller impact in other quarters. On the other hand, in Figure 2, the impact trend for the Anticipatory mode exhibits that this mode has the largest impacts at quarter 1 and the impacts decrease afterwards – similar to the one for the JIT mode. However, based on the setting of SIM, the first round impact for the Anticipatory mode should situate at one quarter prior to quarter 1, before the lifeline disruption occurs, since they anticipate the future final demand one quarter ahead. This sounds contradictory, because many disaster situation is unpredictable, implying difficult to anticipate. This unseen negative impact on the Anticipatory before the disaster occurs can be depicted in Figure 3. Figure 3 presents the trends of cumulative ratio over the static Leontief inverse results (ultimate multiplier effects) for each

Figure 1 Impacts on gross output

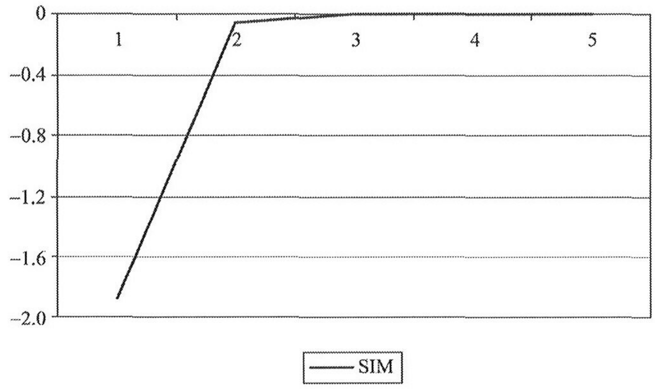


Figure 2 Impacts on gross output by production mode

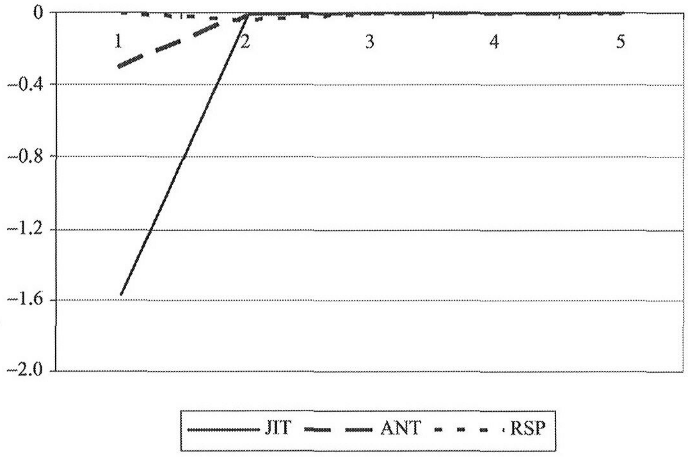
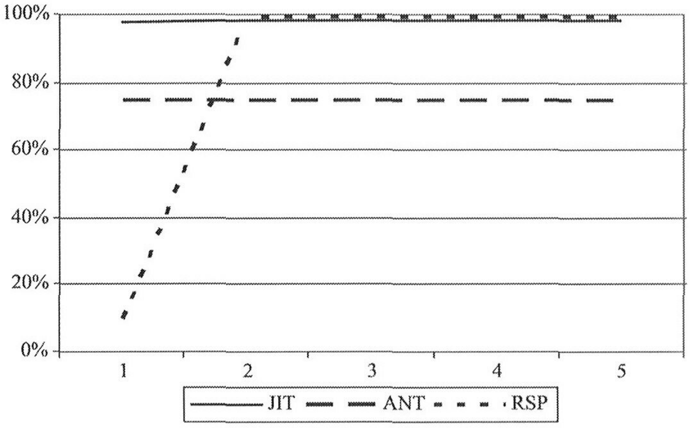


Figure 3 Comparison with the static model by mode (ratio of cumulative impacts over static results)



production mode. As discussed in the previous section with model (15), the static version of SIM will become the standard Leontief inverse model, indicating the ultimate multiplier matrix. Thus, the sum of the temporal multiplier over time from the SIM should converge to the multiplier from the standard Leontief inverse. In Figure 3, the cumulative ratios for the JIT and responsive modes tend to converge to the static Leontief inverse multiplier, with their ratio at quarter 5 being 98.52 percent and 99.68 percent, respectively. On the other hand, the anticipatory mode's trend appears to be flat at the level of 74.86 percent, far from converging to 100 percent. This is due to the fact that the theoretical first round impact for the anticipatory sector occurred at quarter 0, one quarter prior to quarter 1 when the lifeline disruption occurred. What this implies in an empirical sense is that the sectors with anticipatory mode produce their goods at the usual level for the use in quarter 1 during quarter 0, without knowing (or anticipating) the occurrence of the lifeline disruption (a disaster) in the beginning of quarter 1, in which the final demand and thus most intermediate demand decrease due to the lifeline disruption and the production constraints. The sectors in anticipatory mode will face the sudden increase in their inventory as the gap between anticipated and actual (decreased) intermediate demands. This is identified as the "surprise effect" of a disaster in the previous study (Okuyama *et al.*, 2001), and is usually not accounted as economic impact. While this sudden inventory increase in Anticipatory mode can be consumed by the also-sudden increase in demand due to the potential recovery activities, this offsetting consumption may happen only later during the recovery period. This time lag between increased inventory and reconstruction demand injections creates some supply-demand mismatch for some duration right after the occurrence of the disaster. Further analysis of this time lag is necessary to investigate how this temporal supply-demand mismatch influences the overall economic activities in a system. In order to do so, the inventory function in the SIM needs to be specified.

5. Summary and conclusions

In this study, spatial and temporal dimensions of economic impacts of a disaster are investigated and some modeling frameworks to analyze them are presented based on the conventional input-output framework. The simplicity of input-output framework and its relative data availability make input-output analysis useful for empirical and hypothetical analysis of economic aspect of disasters. With the modifications presented in this study, a simple input-output model becomes a more effective tool to address and analyze the spatial and temporal dynamics of impact propagations of a disaster. With a catastrophic disaster like the Great Hanshin earthquake, a disaster becomes a multi-region and a long-term event; it affects other regions' economic activities and the impacts may sustain for a long time. For the planning of the reconstruction and recovery from a disaster, these two dimensions, space and time, are the most critical factors in order to allocate resources effectively and efficiently.

While the sensitivity analysis using more disaggregated input-output model and more detailed set-up and assignment of production mode is required for drawing any policy implications from the case study results, the following two points should be addressed. First, recovery and reconstruction activities after a disaster need to be planned and phased so that no significant supply constraints of intermediate goods to construction sector occur. Different stage of reconstruction activities requires different intermediate inputs. Hence, a policy toward smooth recovery requires prioritizing the reconstruction activities and scheduling to distribute them to different stages of construction phase in order not to create severe supply constraints of intermediate goods and primary inputs. Secondly, with the rich information on interindustry relationships embedded in interregional input-output table, temporal key sector analysis can be accomplished under a disaster situation for illustrating which sectors are more crucial for economy-wide recovery, in a particular stage of reconstruction. Although it may be difficult to concentrate on the recovery of particular sectors after a catastrophic disaster, this type of information can be utilized for creating retrofit priority to make the key sectors less vulnerable.

Notes

1. Most of the services industries can be considered as just-in-time production mode, in which the production takes place and the goods delivered, as the order is placed. However, just-in-time production mode can be considered a special case of responsive production mode when ordering lead time and production interval are minimal, as shown in later part of this section.
2. For responsive production mode, it is more likely to have input inventory; however, in this formulation (Romanoff and Levine, 1990a, b), assuming just-in-time production for simplicity, input inventory is not considered in either mode. However, the production inventory of anticipatory industries can work as the input inventory for responsive industries, although it may not fully reflect the complexity of real world production process.

References

Batey, P.W.J. and Madden, M. (1983), "The modelling of demographic-economic change within the context of regional decline: analytical procedures and empirical results", *Socio-Economic Planning Sciences*, Vol. 17, pp. 315-28.

Boisverst, R. (1992), "Indirect losses from a catastrophic earthquake and local, regional, and national interest", *Indirect Economic Consequences of a Catastrophic Earthquake*, National Earthquake Hazards Reduction Program, Federal Emergency Management Agency, Washington, DC, pp. 207-65.

Chang, S. (1983), "Disasters and fiscal policy: hurricane impact on municipal revenue", *Urban Affairs Quarterly*, Vol. 18 No. 4, pp. 511-23.

Cochrane, H.C. (1974), "Predicting the economic impacts of earthquakes", in Cochrane, H.C., Haas, J.E., Bowden, M.J. and Kates, R.W. (Eds), *Social Science Perspectives on the Coming San Francisco Earthquake*, Natural Hazards Research Paper No. 25, NHRAIC, University of Colorado, Boulder, CO.

Cochrane, H.C. (1995), "Forecasting the economic impact of a midwest earthquake", in Jones, B.G. (Ed.), *Economic Consequences of Earthquakes: Preparing for the Unexpected*, National Center for Earthquake Engineering Research, Buffalo, NY, pp. 223-47.

Cochrane, H.C. (1999), "Indirect economic losses, in Earthquake Loss Estimation Methodology: HAZUS99 Technical Manual", Volume 3, Federal Emergency Management Agency, Washington, DC, pp. 16.1-16.63, available at: www.fema.gov/hazus/dl_tech3.pdf

Cole, S. (1988), "The delayed impacts of plant closures in a reformulated leontief model", *Papers in Regional Science Association*, Vol. 65, pp. 135-49.

Cole, S. (1989), "Expenditure lags in impacts analysis", *Regional Studies*, Vol. 23 No. 2, pp. 105-16.

Dorfman, R., Samuelson, P.A. and Solow, R.M. (1958), *Linear Programming and Economic Analysis*, McGraw-Hill, New York, NY.

Ellson, R., Milliman, J.W. and Blaine Roberts, R. (1984), "Measuring the regional economic effects of earthquakes and earthquake predictions", *Journal of Regional Science*, Vol. 24 No. 4, pp. 559-79.

Goodwin, R.M. (1947), "Dynamical coupling with especial reference to markets having production lags", *Econometrica*, Vol. 15, pp. 181-204.

Gordon, P. and Richardson, H. (1996), *The Business Interruption Effects of the Northridge Earthquake*, Lusk Center Research Institute, University of Southern California, Los Angeles, CA.

Guimaraes, P., Hefner, F.L. and Woodward, D.P. (1993), "Wealth and income effects of natural disasters: an econometric analysis of Hurricane Hugo", *Review of Regional Studies*, Vol. 23, pp. 97-114.

Israilevich, P.R., Hewings, G.J.D., Sonis, M. and Schindler, G.R. (1997), "Forecasting structural change with a regional econometric input-output model", *Journal of Regional Science*, Vol. 37, pp. 565-90.

Kawashima, K., Sugita, H. and Kanoh, T. (1991), "Estimation of earthquake induced economic damage", *Report of Public Works Research Institute*, Vol. 186, pp. 1-57 (in Japanese).

Kuenne, R.E. (1963), *The Theory of General Economic Equilibrium*, Princeton University Press, Princeton, NJ.

Leontief, W. (1951), *The Structure of American Economy, 1919-1939*, 2nd ed., Oxford University Press, New York, NY.

Leontief, W. (1953), "Dynamic analysis", in Leontief, W., Chenery, H.B., Clark, P.G., Duesenberry, J.S., Ferguson, A.R., Grosse, A.P., Grosse, R.N. and Holzman, M. (Eds), *Studies in the Structure of the American Economy: Theoretical and Empirical Explorations in Input-Output Analysis*, Oxford University Press, New York, NY.

Leontief, W. (1970), "The dynamic inverse", in Carter, A.P. and Brody, A. (Eds), *Contributions to Input-Output Analysis*, North-Holland Publishing, Amsterdam, pp. 17-46.

Levine, S.H. and Romanoff, E. (1989), "Economic impact dynamics of complex engineering project scheduling", *IEEE Transactions Systems, Man, and Cybernetics*, Vol. 19, pp. 232-40.

Miller, R.E. and Blair, P.D. (1985), *Input-Output Analysis: Foundations and Extensions*, Prentice-Hall, Englewood Cliffs, NJ.

Ministry of International Trade and Industry (MITI) of Japan (1990), *1985 Interregional Input-Output Tables*, MITI, Tokyo.

Miyao, T. (1995), "Reconstruction boom after the Great Hanshin Earthquake won't arise", *Economist*, 7 March, pp. 26-30 (in Japanese).

Miyazawa, K. (1976), *Input-output Analysis and the Structure of Income Distribution*, Springer-Verlag, New York, NY.

Morishima, M. (1964), *Equilibrium, Stability and Growth*, Clarendon Press, Oxford.

Okuyama, Y., Hewings, G.J.D. and Sonis, M. (1999a), "Economic impacts of an unscheduled, disruptive event: a Miyazawa multiplier analysis", in Hewings, G.J.D., Sonis, M., Madden, M. and Kimura, Y. (Eds), *Understanding and Interpreting Economic Structure*, Springer-Verlag, New York, NY, pp. 113-44.

Okuyama, Y., Hewings, G.J.D. and Sonis, M. (2001), "Economic impacts of unscheduled events: sequential interindustry model (SIM) approach", paper presented in the North American Meetings of Regional Science Association International, Charleston, SC.

Pyatte, G. and Roe, A.R. (1977), *Social Accounting for Development Planning*, Harvard University Press, Cambridge, MA.

Romanoff, E. (1984), "Interindustry analysis for regional growth and development: the dynamics of manpower issues", *Socio-Economic Planning Sciences*, Vol. 18 No. 5, pp. 353-63.

Romanoff, E. and Levine, S.H. (1977), "Interregional sequential interindustry modeling: a preliminary analysis of regional growth and decline in a two region case", *Northeast Regional Science Review*, Vol. 7, pp. 87-101.

Romanoff, E. and Levine, S.H. (1981), "Anticipatory and responsive sequential interindustry models", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 11 No. 3, pp. 181-6.

Romanoff, E. and Levine, S.H. (1986), "Capacity limitations, inventory, and time-phased production in the sequential interindustry model", *Papers of the Regional Science Association*, Vol. 59, pp. 73-91.

Romanoff, E. and Levine, S.H. (1990a), "Combined regional impact dynamics of several construction megaprojects", *Regional Science Review*, Vol. 17, pp. 85-93.

Romanoff, E. and Levine, S.H. (1990b), "Technical change in production processes of the sequential interindustry model", *Metroeconomica*, Vol. 41 No. 1, pp. 1-18.

Romanoff, E. and Levine, S.H. (1991), "Technical change and regional development: some further developments with the sequential interindustry model", in Boyce, D.E., Nijkamp, P. and Shafer, D. (Eds), *Regional Science:*

Retrospect and Prospect, Springer-Verlag, Berlin, pp. 251-75.

Romanoff, E. and Levine, S.H. (1993), "Information, interindustry dynamics, and the service industries", *Environmental and Planning A*, Vol. 25, pp. 305-16.

Rose, A. and Benavides, J. (1998), "Regional economic impacts", in Shinozuka, M., Rose, A. and Eguchi, R.T. (Eds), *Engineering and Socioeconomic Impacts of Earthquakes*, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, pp. 95-123.

Rose, A., Benavides, J., Chang, S.E., Szczesniak, P. and Lim, D. (1997), "The regional economic impact of an earthquake: direct and indirect effects of electricity lifeline disruptions", *Journal of Regional Science*, Vol. 37 No. 3, pp. 437-58.

Stone, R. (1961), "Social accounts at the regional level", in Isard, W. and Cumberland, J.H. (Eds), *Regional Economic Planning*, OECD, Paris, pp. 263-9.

ten Raa, T. (1986), "Dynamic input-output analysis with distributed activities", *Review of Economics and Statistics*, Vol. 68 No. 2, pp. 300-10.

West, C.T. and Lenze, D.G. (1994), "Modeling the regional impact of natural disaster and recovery: a general framework and an application to Hurricane Andrew", *International Regional Science Review*, Vol. 17 No. 2, pp. 121-50.

Wilson, R. (1982), *Earthquake Vulnerability Analysis for Economic Impact Assessment*, Information Resources Management Office, Federal Emergency Management Agency, Washington, DC.