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1 author:

Yasuhide Okuyama
Kitakyushu University

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By

Yasuhide Okuyama

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Yasuhide Okuyama
Regional Research Institute, West Virginia University
511 N. High Street Morgantown, WV 26506-6825 USA

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THE ECONOMICS OF NATURAL DISASTERS: A CRITICAL REVIEW

Yasuhide Okuyama

Regional Research Institute, West Virginia University, Morgantown, WV 26506-6825, yaokuyama@mail.wvu.edu

Abstract:

Significant progress has been made in recent years for modeling spatial economic impacts of disasters in a regional context (for example, Okuyama and Chang eds. *Modeling the Spatial Economic Impacts of Disasters*, forthcoming). While these advancements are more toward modeling strategies based on conventional frameworks, little has been dealt with the theory on economics of disasters, since the pioneering work by Dacy and Kunreuther (*The Economics of Natural Disasters*, 1969). In this paper, "The Economics of Natural Disasters" is reviewed and updated for providing a theoretical perspective toward disaster related research. The review is carried our through restructuring the framework of Dacy and Kunreuther with new findings from the recent studies and extending it to a regional context. In addition, the paper proposes the research directions for constructing further the theory on economics of disaster.

1. Introduction

Significant progress has been made in recent years for economic analysis of natural disasters, especially in the field of modeling spatial economic impacts of disasters in a regional context (for example, Okuyama and Chang eds. *Modeling the Spatial Economic Impacts of Disasters*, 2004). While these advancements are empirical analysis oriented and toward modeling strategies based on conventional framework, little has been dealt with the theory on economics of natural disasters, since the pioneering work by Dacy and Kunreuther (*The Economics of Natural Disasters*, 1969). Some others (for example, Sorkin, 1982; and Albala-Bertrand, 1993, among others) aim to offer the generalized framework of disaster analysis, but they are yet oriented to investigate empirical cases and/or to provide the empirical modeling frameworks for the analysis, and lack the theoretical development and/or analysis of disasters and their impacts to economy. This may be due to the fact that disasters are quite different from other economic events, in terms of its frequency, extent, and predictability. Hence, it may be the case that there might be not sufficient observations to construct a unique theoretical framework for disaster as a phenomenon. Or, it may be considered that disasters can be dealt as, or like, a part of economic frustrations, such as business cycle. However, disasters pose quite a different set of impacts to an economy from other economic phenomena, such as changes in public policy and/or regulation, and oftentimes require a careful treatment of economic behavior changes under the chaotic situation after a disaster.

In this paper, Dacy and Kunreuther's "*The Economics of Natural Disasters*" is reviewed and discussed for providing theoretical perspectives toward disaster related research. In the next section, their theoretical frameworks are reviewed and analyzed. Section 3 extends and discusses their theoretical foundation for the short-term recuperation after a disaster using microeconomic theory. In Section 4, the impacts of long-term recovery are analyzed employing a set of growth models. Section 5 concludes and proposes the research directions for constructing further the theory on economics of natural disasters.

2. Review of *Economic Theory and Natural Disaster Behavior*

The book, "*the Economics of Natural Disasters*", by Douglas C. Dacy and Howard Kunreuther was published in 1969, following the National Flood Insurance Act of the United States in 1968 and devastating losses from the Alaska earthquake in 1964. The authors claimed that the main objective of the book is "to formulate a clear-cut case for the development of a comprehensive system of disaster insurance as an alternative to the current paternalistic Federal policy" (page *ix*). The book consists of four major parts: first, the framework of analysis was set up using various economic theories, based on the general trends of natural disasters and the damages in the United States; the following two parts are the analysis of the empirical evidence for the short-period recuperation and the long-term recovery; and the final part discussed the role of the Federal government in natural disasters, mainly focusing on the need for comprehensive disaster insurance. Empirical evidence parts (Parts II and III) are quite extensive using the historical data then from various disasters in order to support the framework constructed in Part I. The concluding part (Part IV) proposes and analyzes disaster insurance programs, and this particular part on disaster insurance has been extended to a series of papers/books by the authors to this date (for example, Kunreuther *et al*., 1978; Kunreuther, 1996; and Kunreuther and Roth, 1998, among others). While the update of the empirical parts and further discussions of disaster insurance with the recent investigations on insurance in regional economic modeling for disasters (for example, Cochrane, 2004; and Cole, 2004) will be valuable and important, the present paper deals with the theoretical framework that Dacy and Kunreuther discussed in order to shed some lights on the investigation of the economics of disasters.

Chapter 3 of the book is titled “Economic Theory and Natural Disaster Behavior”, discussing and proposing the theoretical analysis of behavior following natural disasters with the following two phases: a) short-term recuperation phase; and 2) long-term recovery problems. In their analysis, the short-term recuperation phase is treated with microeconomic theory, such as decision-making theory and laws of demand and supply, whereas the long-term recovery problems are investigated using macroeconomic theory, such as economic growth theory.

2.1. Analysis of Short-Term Recuperation Phase

Short-term recuperation phase is defined as the emergency response and restoration period after a disaster. In this phase, the information about the disaster *per se*, the damages, and the restoration process for the immediate future become uncertain, and thus create further communication problems. Dacy and Kunreuther raised this information and communication problems on decision making and supply-demand problems for this phase.

Problem of Information and Communication

In and immediately after a disaster, the information regarding the extent and level of damages become, at best, difficult to obtain. These information may become gradually available as the restoration process progresses, but the credibility and accountability of the information, such as the distribution of future demand, will be still unclear. This ‘uncertainty’ of the information is a key to the analysis of decision making in this phase, since most economic models/analyses assume perfect information and/or empirical probabilities of the future events. Therefore, accurate data and effective information about the disaster and damages become even more important in order for making efficient resource allocations under some constraints due to the damages. The following example for resource allocation in public sector right after a disaster was used in the book to illustrate a decision making under uncertainty after a disaster (pp.61-63):

Consider a community just struck by a catastrophic disaster. Community officials need to manage two items, *A* (for example, medical supplies) and *B* (for example, water), both of which are needed for the emergency response period. Suppose that this community has no previous inventory for these items, and that community officials can expect that the interval between an initial and a second shipment of outside aid will be *x* hours. For simplicity, assume that the price of these items and the costs of transportation do not change under an emergency situation. Thus, the community officials are solely concerned with inventory-related expenses, such as storage costs and shortage costs. The book does not provide the details of the shortage cost, but it is assumed as the impact cost of not having a particular item; in other words, the shortage cost implies the value, not price, of having a particular item. Since the problem is set to be the inventory related resource allocation, there is a capacity constraint for storage of the items. Consider that item *B* is twice as large as *A*; hence, the storage cost of *B* is double that of *A*. The community has the limited inventory space for these items, which may hold either 4 units of item *A*, 2 units of item *B*, or some combinations of them. If the unit storage cost of inventory depends on the size, not the weight, of an item, the following relationship will hold:

$$2S_a = S_b \tag{1}$$

where S_a is the unit storage cost for item *A*, and S_b is that of item *B*. If the shortage cost (value) of each item does not change with the usage, the shortage-storage ration of each item can be defined as follows:

$$\left.\begin{aligned} SSR_a &= {SHC_a}/{S_a} \\ SSR_b &= {SHC_b}/{S_b} = {SHC_b}/{2S_a} \end{aligned}\right\} \tag{2}$$

where SSR_k is the shortage-storage ratio of item *k*, SHC_k is the shortage cost of item *k*. In order to calculate how many of each item are needed for emergency response after a disaster, community officials need to estimate the probability that the *i*th unit of an item will be used. Suppose the community officials can assign some probabilities of usage for each item as follows: P_a^i is the probability of used of *i*th unit of *A*, and P_b^j is that of *j*th unit of *B*. With these assumptions, the resource allocation problem of this community can turn to be a maximization problem of the following objective function:

$$\max \quad \sum_i V_a^i + \sum_j V_b^j \tag{3}$$

$$\textit{subject to} \quad i \cdot S_a + j \cdot S_b \leq 4S_a \qquad \text{[capacity constraint]}$$

where V_a^i is the relative value of *i*th unit of *A*, and V_b^j is the relative value of *j*th unit of *B*., which are defined as follows:

$$\left.\begin{aligned} V_a^i &= P_a^i \times SSR_a \\ V_b^j &= P_b^j \times SSR_b \end{aligned}\right\} \tag{4}$$

Also, using the relationship (1), the capacity constraint will collapse to the following form:

$$i + 2j \leq 4 \tag{5}$$

This is rather a simple programming problem, if all the assumptions of information availability hold. However, only certain value and relationship in this setting is (1), the relationship between each item's storage cost, and thus the capacity constraint, (5). All other variables are unknown before a disaster occurs. In particular, shortage cost (value) of each item, SHC_k, depends on types of the damages that a disaster brought. If a significant number of people are injured, item *A* (medical supply) may be valued much higher than item *B* will be. On the other hand, if the lifeline (water) in the community is damaged but no casualties or injuries in the community, item *B* will be valued higher. Likewise, the probability of usage of each item, P_k^i, depends well on the extent of the damages. These types and extend of damages vary across different types of disaster and are quite uncertain and very problematical to estimate during the emergency phase after a disaster. Therefore, without these information, the objective function, (3) here is almost impossible to solve when it is needed to be solved (estimation of the initial order of aid). In this sense, the real-world problem is much more complicated than Dacy and Kunreuther defined, although they acknowledge this drawback (page 63). In order to improve this type of decision making model for emergency response, the concept of uncertainty and risk is further discussed in the following section.

Supply and Demand Problems

The analysis of supply and demand relationship in and after a disaster in the book starts with a provocative paragraph:

> "At first glance, a theorist might view these short-term problems as trivial applications of the basic laws of supply and demand, thus concluding they are not worth special study. He might claim that if the disaster decreases the stock of a certain commodity, while demand remains either the same as before the event or increases, then price should rise, other things being equal. Because the *ceteris paribus* conditions might not hold in these extreme situations, the supply and demand curves may shift in unexpected ways." (page 64)

In order to prove their point, Dacy and Kunreuther used three cases of supply-demand changes. Case I is noted as "No Outside Aid—No Sympathy", simulating the theorist view in the first half of the above paragraph. Case II adds the aid from the outside, indicating the changes in demand side that anticipate the aid from the outside. Case III is more to their point, including a sympathetic feeling within the damaged region, leading to mutual aid. Their point in Cases II and III is that the price may not become such higher as in the simple analysis of the theorist, but rather lower than expected due to the outside aid and/or sympathetic behavior of mutual aid. These phenomena have been observed: for example, after the Kobe Earthquake in Japan, 1995, the consumer price index in Kobe actually somewhat decreased in the first month and was relatively stable afterwards. The sympathetic behavior of mutual aid in a chaotic situation has been also observed: recent examples include after the September 11th terrorist attacks of New York City in 2001 and the US North East black out in 2003. These types of behavior may not be limited to consumption behavior of the final demand, but also will apply to inter-industry relationships. For example, after the Kobe earthquake, one of the critical suppliers to the Toyota Motor Corporation in Japan was severely damaged and could not provide the parts to Toyota. A usual economics response to this type of supply constraints is to find another supplier for this particular parts with possibly higher price (due to excess demand). On the contrary, Toyota stopped their entire assembly lines in Japan, and sent their engineer to that particular supplier for repairing the damaged factory. The stoppage of Toyota assembly lines lasted only three days. This may be an extreme case, since Toyota has been known for their very close relationship with the suppliers. However, in a chaotic situation, many will behave somewhat differently as usual, creating further complicated economic activities after a disaster. On this point, Dacy and Kunreuther showed some simple but suggestive examples here.

2.2 Analysis of Long-Term Recovery Problems

Dacy and Kunreuther defined the long-term recovery as: “long-term recovery refers to the rebuilding process that brings the community back to its predisaster economic level (page 70).” They further clarify this definition as: “we will assume that residents desire to be in at least the same position following the disaster as they were before (page 71).” The latter definition is an extension of the former, since the latter includes the possibility that the community can recover and grow beyond its predisaster economic level. As they noted on page 71, “little attention has been given to the (long-term) reconstruction problems of a stricken community.” This may be due to the fact that the long-term recovery of the damaged community can be influenced from many other factors, such as macroeconomic influences from the nation, business cycle, and so forth. Also, most economic impact studies of disasters have dealt with the recovery of medium-run (within one year) moving toward the predisaster level rather than that of long-run (beyond one year after a disaster) leading to a new equilibrium (Rose, 2004b). It is also true that most economic models for disaster are flow model measuring the impacts on economic flows rather than stock model evaluating the damages on stocks and the recovery (Rose, 2004a). Therefore, their claim of the absence of the long-term recovery analysis can be rephrased to the lack of the capital (stock) recovery analysis after a disaster.

This dearth of stock recovery analysis may be resulted from the following two major reasons. First, the disturbances to economic flows caused by a disaster are relatively easy to model using the conventional modeling frameworks, such as input-output analysis. On the other hand, the investment decisions to capital (stock) are rather complex, and in addition, investment decision under a disaster situation and the following recovery can be quite different from the usual ones without a disaster. For example, the Kobe factory of the Sumitomo Rubber Industries, Ltd was severely damaged by the Kobe earthquake in 1995; instead of repairing and reconstructing the facility, they decided to torn down the damaged facility and moved to a different region, constructing a new factory there. Without the Kobe earthquake, they may have still used the Kobe factory with gradual update of capital stocks (building and equipments) as an investment decision. A disaster forced them to adopt quite a different environment for decision making. Second, although some disasters can bring enormous damages to a community, in developed nations, the damages to capital stock are rather minor in terms of macroeconomic context. On the other hand, the damages from a catastrophic disaster in a developing nation can become truly devastating, potentially washing out a major portion of capital stock in a nation, such as the 1998 floods in Bangladesh (Shah, 1999). Therefore, it may be more appropriate to investigate the stock damages and the recovery in the developing county context or a regional context, rather than in the national level of developed countries. Their emphasis on stock recovery analysis here is, of course, resulted from the intention to propose disaster insurance program for recovery of damaged capital stocks.

In order to analyze the long-term recovery problems, Dacy and Kunreuther employed a simplified version of Solow-Swan growth model. They divide capital stock, *K*, into three-fold in terms of its use: public capital, K_p, business capital, K_b, and residential capital, K_r. Then, the production function becomes as follows:

$$Y = f\left(K_p, K_b, K_r, L\right) \tag{6}$$

Suppose that following a disaster, capital stock is reduced to K_p^*, K_b^*, and K_r^* for each type of capital stock. For simplicity, it is assumed that the levels of labor and outside aid for capital recovery are fixed at $\bar{L}$ and $\bar{K}$, respectively. Then, during the recovery from disaster damages, the production function, (6), is transformed to the following form:

$$Y = f\left(K_p^*, K_b^*, K_r^* \mid \bar{L}, \bar{K}\right) \tag{7}$$

Then, the fixed labor and outside aid, $\bar{L}$ and $\bar{K}$, need to be allocated to recover damaged capital in order to maximize the total output, *Y*. Thus, "(t)he optimum process of recovery can be determined directly from the marginal productivity conditions. At any moment of time, resources will be utilized in restoring the facilities whose contributions to overall productivity are the greatest (pp. 74-75)."

With this formulation, it is possible to investigate the resource allocation of the aid across the different types of capital stock so that, as they claimed, the optimum path of recovery can be analyzed. Uncertainty of the information availability for the damages to capital stocks during the emergency response period becomes less significant in this case, since the damage information become available in the long-run. It may become more useful if the model specifies the relationships of productivity between the different types of capital. For example, public capital, K_p, such as infrastructure and lifelines, can have a significant improvement to the productivity of undamaged business capital, K_b, and to the recovery process (accumulation process after a disaster) of both damaged business capital and residential capital, K_b and K_r.

Another potential improvement to this formulation is to include technological progress explicitly. Recent emphasis on endogenous growth theory (Barro and Sala-I-Martin, 1995, and Aghion and Howitt, 1998, for example) indicates that modeling technological progress endogenously is essential to advance growth models toward further sophisticated structure. The endogenous technological progress has been studies for a long-run growth and in an equilibrium oriented context, but without or not under a catastrophic disturbance, *i.e.* a disaster. As mentioned above, if capital stocks are damaged in a disaster, the decision making to replacement, or recovery, of the damaged capital can be quite different from the one under a no-disaster situation. Empirical observations indicate that older facilities and equipments are more prone to receive severe damages than newer ones, and they will be replaced with newer, or sometimes the state-of-the-art, facility and equipments. This technology replacement, rather than technological progress, can be considered as a positive jump in technology level for production process (Okuyama *et al*., 2004), and may have sizeable impacts on the growth path after a disaster. Because of the suddenness and promptness of technology replacement, it may be easier to deal with it as an exogenous shock to technological progress. Disasters in the growth theory context are further discussed in Section 4.

3. Value of Information: Risk and Uncertainty

As discussed in 2.1, the information about the extent and level of damages from a disaster are critical, especially for the resource allocation in emergency response period. However, obtaining these information are often limited, or the obtained information can be incorrect and/or fabricated due to the chaotic nature of aftermath in a disaster. These situations are often referred to 'uncertainty' of information, and may create further disturbances in economic activities and decision makings. While dealing with uncertainty is important for economic analysis of a disaster, few studies in the disaster related literature have explicitly dealt or incorporated with this uncertainty of information and its effects.

The concepts of risk and uncertainty have been used in the disaster related literature, but they are often used in an unclear manner. In the mainstream economics, risk and uncertainty have been discussed since the Frank H. Knight's (1921) famous distinction between risk and uncertainty was made. In Knight's view, 'risk' refers to situations where the decision-maker can assign mathematical (objective) probabilities to the randomness which s/he is faced with, whereas 'uncertainty' refers to situations when this randomness cannot be expressed in terms of specific mathematical probabilities. According to the History of Economic Thought Website (http://cepa.newschool.edu/het/home.htm), many economists dispute this Knight's distinction, claiming that Knightian risk and uncertainty are one and the same thing. Their main argument is that uncertainty is a problem of knowledge of the relevant probabilities, not of their existence. Nonetheless, some economists, particularly in the Post Keynesian school, such as Shackle (1979) and Davidson (1991), have argued that Knight's distinction is so critical that Knightian uncertainty may be the only relevant form of randomness for economics, in particular, when it is tied up with the issue of time and information, while Knightian risk is only possible in very controlled scenarios with very clear alternatives, such as gambling. Based on these 'risk versus uncertainty' debate, the History of Economic Thought Website proposed a modified version of Knightian distinction, in which theories are divided into those use the assignment of mathematical probabilities and those do not make such assignment. In this manner, the expected utility theory of von Neumann and Morgenstern (1944) is one of 'risk' schools, where as the state-preference approach of Arrow (1953) and Debreu (1959) are one of 'uncertainty' schools. Savage's (1954) theory that employs 'expected utility with subjective probabilities' can be placed as intermediate theory in this context.

In the disaster literature, risk and uncertainty are employed without any significant debate of their definitions. Dacy and Kunreuther used 'uncertainty' for the decision making analysis during emergency response period, describes in the subsection of *Problem of Information and Communication*. However, based on the Knightian distinction, their model is clearly a risk model with objective probability for item usage, or perhaps, it might be somewhat connected to

Savage's 'expected utility with subjective probabilities'. In any case, they did not explicitly discuss how the decision makers derive those probabilities. Oftentimes, in the disaster literature with engineering emphasis, the term 'risk' is used for probability of a disaster occurrence or of the damages from a disaster (for instance, Oppenheim, 1980; Nordenson, 1997; Johnson and Eguchi, 1998). In particular, Oppenheim's paper is titles as "Lifeline Seismic Risk: Decisions under Uncertainty" and makes no explicit distinctions between risk and uncertainty. It appears in his paper that 'uncertainty' is used for describing the situation created by a disaster and 'risk' is used for defining the probabilistic occurrence of a specific event (damage). In this sense, he considered that 'uncertainty' is a broader definition of 'risk'. In the disaster studies emphasizing more on economic theory, on the other hand, many employed also the probabilistic occurrence of a disaster as 'risk' in order to derive the expected utility for decision-makings against disasters (for example, Howe and Cochrane, 1976; Brookshire, *et al*., 1985; Boisvert, 1992; and Kunreuther and Roth, 1998). In these studies, more attention are directed toward pre-disaster analysis, such as risk management and disaster insurance, rather than toward the uncertainty created after a disaster.

With the Knightian distinction, it can be considered that most of the above studies employ solely the concept of 'risk', but not 'uncertainty'. In order to clarify the terms and their use and to define the terms fit well and useful with disaster related research, it can be assumed that 'risk' refers to the occurrence of disasters or damages where decision-makers can assign mathematical probabilities for the randomness in a predisaster context whereas 'uncertainty' refers to the situations in the aftermath of a disaster where the situations and consequences cannot be expressed in terms of specific mathematical probabilities in a postdisaster context. In this way, 'risk' used in most studies, including the above, can retain its definition and can also have the solid distinction with 'uncertainty'. A major difference from the Knightian definition of 'uncertainty' is that the degree and extent of 'uncertainty' after a disaster is not fixed—as emergency response and recovery starts, more information regarding the damages and recovery plan will become available; thus, the degree and extent of 'uncertainty' may diminish (see Figure 1). In a normal period before a disaster, some, but not significant, level of uncertainty may exist, such as business cycle and momentary fluctuations; at the time of disaster, the degree of uncertainty jumps up to a very high level, due to no information available about the extent of the damages on capital stocks and labor. This high level of uncertainty may continue in a short period, due to the continued lack of information and also to the confusion and depression under a chaotic situation created by the disaster. The length of this period depends on the size of the disaster and the extent of the damages. After this period, the information regarding the level and extent of damages become available; thus, the level of uncertainty may start declining. However, the speed of this decline can be influenced by many factors, such as the release timing of recovery plan, the priority of recovery, the damages to the other regions, etc. These uncertainties are difficult to be quantified with objective mathematical probabilities, and are also difficult to be measured even with the subjective-preference.

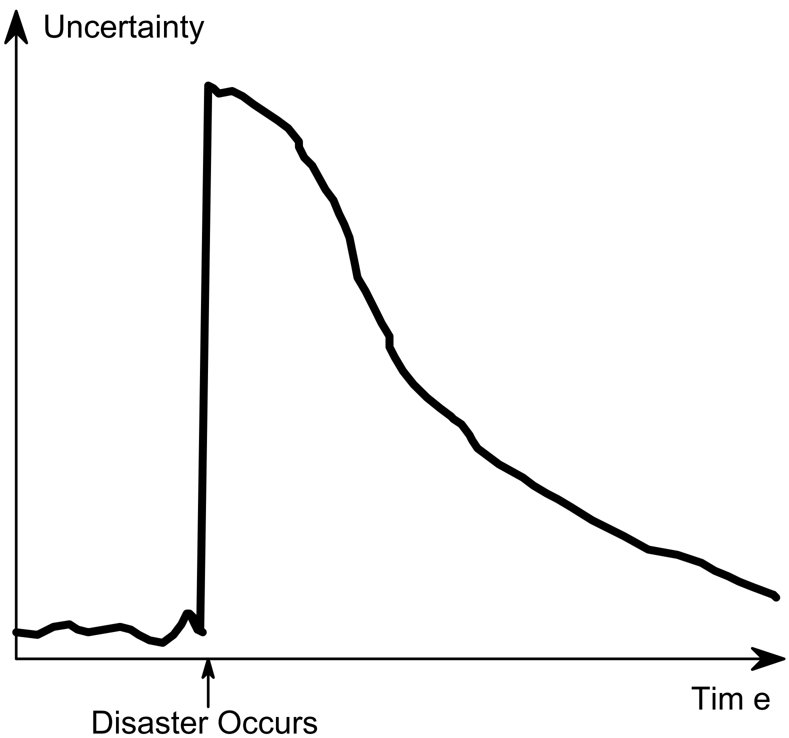

Figure 1. Degree of Uncertainty in and after a Disaster

This uncertainty after a disaster can create some serious impacts to economic activities in terms of production planning (Okuyama *et al*., 2004). Dacy and Kunrauther's way to cope with this uncertainty as 'value of information' is useful mostly to promote pre-disaster preparedness. However, in order to evaluate the economic impacts of a disaster, it is important to include the effects of this uncertainty, since uncertainty may create further disturbances and influences to decision-making for economic activities and recovery than most impact studies without it derived. Furthermore, during this uncertain period, other behavioral factors that are not common without a disaster, such as sympathy (Dacy and Kunreuther, 1969) and postdisaster cooperation (De Alessi, 1975), and changes in consumption behavior (Okuyama *et al*., 1999), need to be considered to evaluate the full spectrum of impacts and the recovery process and path after a disaster. Dealing with and incorporating with these complexities is a challenge for impact study of a disaster.

4. Effects of a Disaster on Long-Term Growth

Catastrophic disasters create significant and intense damages to the capital stocks, and sometimes to the labor (for example, more than 6,000 casualties in the Kobe earthquake, 1995). While these damages are serious and extensive, as discussed in Section 2, the effects of these damages to the long-term economic growth of a developed county are still limited (Okuyama *et al*., 1999). However, these damages become quite serious in the context of regions and of developing countries. Dacy and Kunreuther's discussion using a simple growth theory was important since, even in the developed economy context, it can provide useful information toward the resource allocation for recovery activities. In this section, the effects of a disaster in growth theory context is analyzed and discussed, in order to offer some insights for the effects of a disaster to the transition of long-term growth.

For simplification, a basic Neo-Classical model of the Solow-Swan model (Solow, 1956; and Swan, 1956) is employed in this paper[1]. Consider, for a moment, if technological progress can be neglected[2], the production function of an economy can be set as:

$$Y = F(K, L) \tag{8}$$

[1] The following discussion can be extended to more sophisticated model of Endogenous Growth models. The application to Endogenous Growth model can provide further analysis for the long-term impacts of a catastrophic disaster.
[2] This assumption of 'no technological progress' will be relaxed later in this section.

where *Y* is the total output, *K* is the level of capital accumulation, and *L* is the level of labor population. The use of per capita term for output and capital makes Equation (8) the intensive form:

$$y = f(k) \tag{9}$$

where $y = {}^{Y}\!/_{L}$, and $k = {}^{K}\!/_{L}$. Set that saving rate (constant) is *s*, capital depreciation is δ (constant), and population growth rate is *n* (constant). The change in per capita capital stock over time becomes as follows:

$$\dot{k} = s \cdot f(k) - (n + \delta) \cdot k \tag{10}$$

where $\dot{k} = {}^{dk}\!/_{dt}$. Thus, the steady state level of capital accumulation, k^*, where $\dot{k} = 0$, satisfies the following condition:

$$s \cdot f(k^*) = (n + \delta) \cdot k^* \tag{11}$$

This steady state condition can be seen as the point **A** in Figure 2. Now, suppose that an economy is at the steady state[3] and that a catastrophic disaster occurred and the capital stocks were severely damaged, but no casualties in labor population; thus the per capita capital level went down to the decreased level, k_d, where $k_d < k^*$. This economy's output decreased, due to the damages from a disaster, from the steady state level, y^*, to the damaged level, y_d. Because of the damages and the decreased level of per capita capital stock, the economy is now out of its steady state, and has some space (the distance between points **B** and **C**) for the growth (recovery) of per capita capital accumulation. Therefore, the economy picks up a speed to increase the level of per capita capital from k_d toward k^*, as the recovery process. At the same time, during the recovery period, resources (output) are allocated more toward the reconstruction of damaged capital stocks than under the normal circumstances without a disaster. This implies that the saving rate for the capital accumulation may become higher than the previous level, *s*. This recovery saving rate is set as s_r (where $s_r > s$), may accelerate the speed of recovery, capital re-accumulation, further (the distance between **D** and **C**, which is much wider than between **B** and **C**), as shown in Figure 2. However, as the economy recovers, the recovery saving rate should

[3] Even if an economy is not at the steady state, the framework and the results of the following analysis still apply.

gradually go back to the normal rate, s, and as the level of capital accumulation becomes close to the steady state level, k^* (**D** to **A** in Figure 2), the speed of recovery is close to zero.

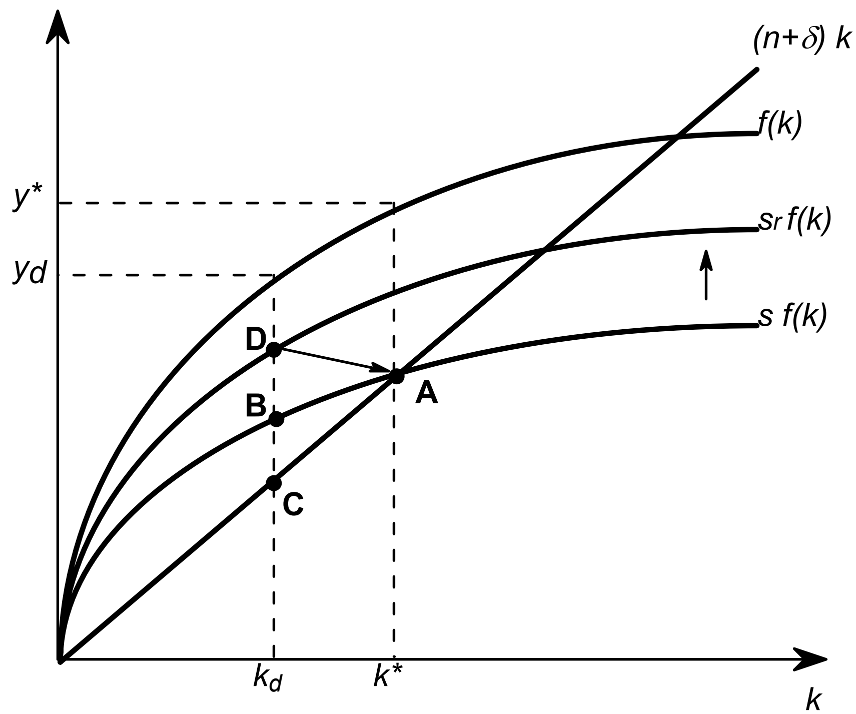

Figure 2. Solow-Swan Model and a Disaster Situation

The transitional dynamics of recovery can be further illustrated by the use of the growth rate of *k*. The growth rate of *k*, γ_k, can be given based on Equation (10):

$$\gamma_k \equiv \dot{k}/k = s \cdot f(k)/k - (n+\delta) \qquad (12)$$

Figure 3 indicates the transitional dynamics around the steady state of the Solow-Swan model. At the steady state, k^*, the growth rate becomes zero due to the intersection of two lines, $s \cdot f(k)/k = (n+\delta)$. With a catastrophic disaster, the level of per capita capital becomes k_d, and due to this departure from the steady state, the growth rate of *k* becomes positive (the distance between **B** and **C** in Figure 3). As in the above, because of the intense reconstruction activities, the saving rate becomes higher (to s_r). Consequently, the growth rate of *k* becomes much higher (the distance between D and C). As the reconstruction progresses, the saving rate gradually returns to the previous level, *s*, and the growth rate of *k* moves back to the steady state level of zero (from **D** to **A** in Figure 3). Based on these results, it can be concluded that the more resources are allocated for the recovery and reconstruction, the faster the speed of recovery (capital re-accumulation). This may change with the inclusion of technological progress.

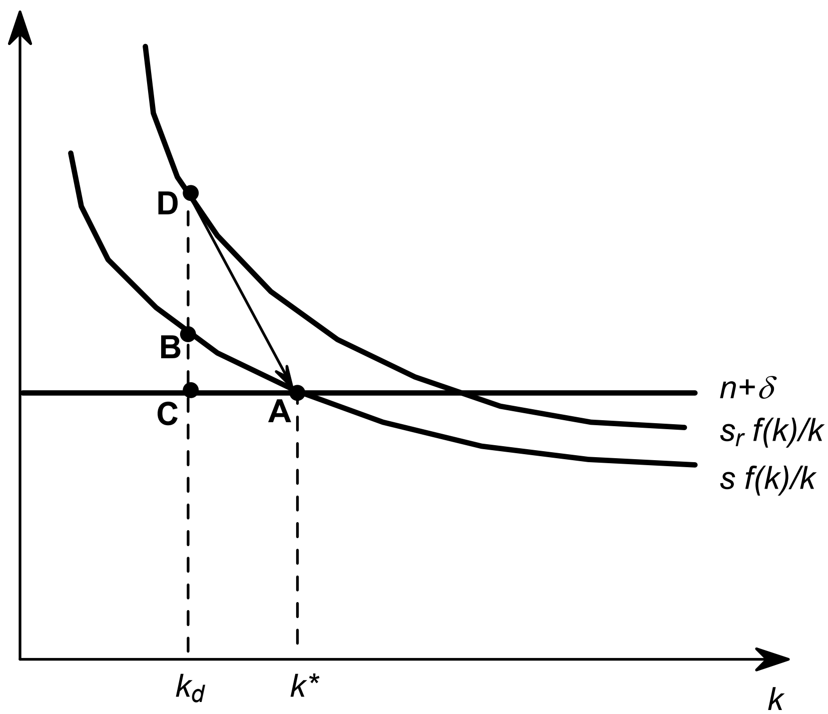

Figure 3. Dynamics of Recovery

As discussed in Section 2.2, the damages of a catastrophic disaster fall more often to the older and outdated facilities and equipments than to the new and updated ones, because mainly of the weaker structure and the outdated regulations (for instance, building code) applied for older capital stocks. With the recovery activities, these damaged older facilities and equipments are updated and upgraded to newer facilities and equipments, which may be built upon and use newer technologies. Suppose that the level of technology in an economy is the aggregated technological level that consists of a mixture of old and new capital stocks, and that the recovery activities increase the rate of technological progress to some extent by updating the technological level of damaged older capital (Figure 4). This increase of the rate of technological progress is strictly temporary, since the recovery activities cannot progress the level of technology *per se*. Following the example of the Solow-Swan model with labor-augmenting technological progress by Barro and Sala-i-Martin (1995; pp. 34-36), it is assumed that the level of technology, $A(t)$, grows at the constant rate, x, over time under the normal circumstances, but grows at a somewhat faster rate, x_r ($x_r > x$), due to the technological replacement, during the recovery period, as shown in Figure 4.

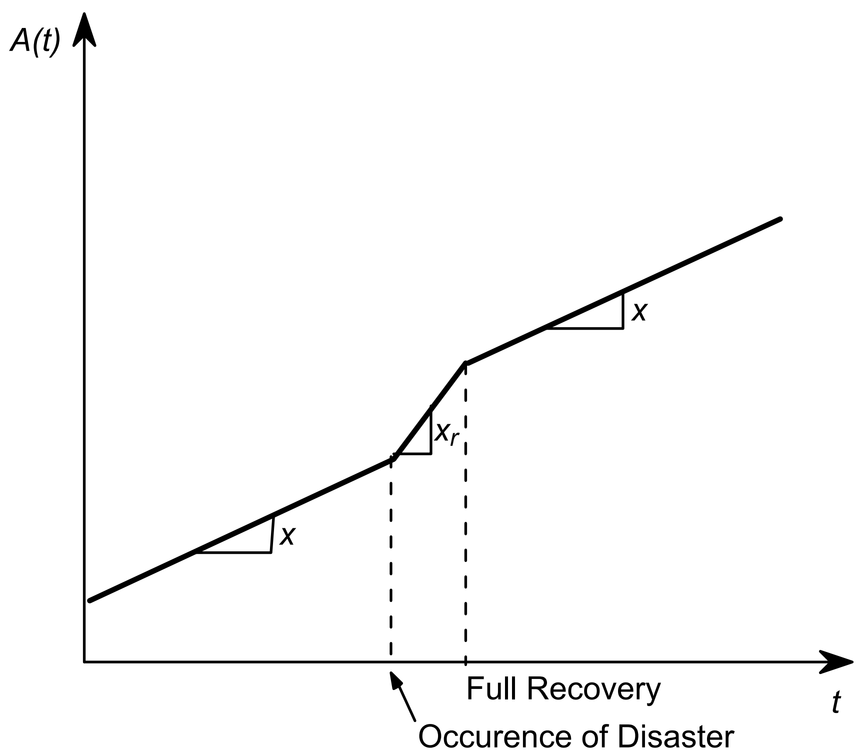

Figure 4. Technological Progress and a Disaster

With this technological progress, the previous model in Equations (8) and (10) now becomes:

$$Y = F\left[K, L \cdot A(t)\right] \tag{13}$$

$$\dot{k} = s \cdot f\left[k, A(t)\right] - (n + \delta) \cdot k \tag{14}$$

To analyze the transitional dynamics of this model with technological progress, it is convenient to rewrite the model using the *effective amount of labor*, $\hat{L} \equiv L \cdot A(t)$, the labor population multiplied by its efficiency, $A(t)$. Then, the quantity of capital per unit of effective labor, $\hat{k}$, can be defined as:

$$\hat{k} \equiv K/\hat{L} = K/[L \cdot A(t)] = k/A(t) \tag{15}$$

With the quantity of output per unit of effective labor, $\hat{y} \equiv Y/\hat{L}$, the intensive form of the model becomes:

$$\hat{y} = f(\hat{k}) \tag{16}$$

Hence, Equation (14) now becomes:

$$\dot{\hat{k}} = s \cdot f(\hat{k}) - (x + n + \delta) \cdot \hat{k} \tag{17}$$

Also, the growth rate of $\hat{k}$ is:

$$\gamma_{\hat{k}} = s \cdot f(\hat{k}) / \hat{k} - (x + n + \delta) \tag{18}$$

At the steady state, $\hat{k}$ becomes $\hat{k}^*$, since its growth rate becomes zero (see Figure 5):

$$s \cdot f(\hat{k}^*) / \hat{k}^* = (x + n + \delta) \tag{19}$$

As in the previous model with no technological progress, the economy suffers from a catastrophic disaster, and a part of capital stocks are damaged and destroyed; thus, the quantity of capital per unit of effective labor becomes from the steady state level, $\hat{k}^*$, to the damaged level, $\hat{k}_d$. At this point, the growth rate of recovery is the distance between **B** and **C**, if no special allocation of resources to recovery is made. For the faster recovery, the saving rate can be increased to allocate more resources to capital re-accumulation; thus, as in the previous case, the growth rate of $\hat{k}$ becomes much faster—the distance between **D** and **C**. The story up to now is exactly the same as the one for the model without technological progress. However, it is assumed, in Figure 4, that the technological replacement can increase the rate of technological progress during the recovery period. This increase is reflected as an upward shift of $x+n+\delta$ to $x_r+n+\delta$. Because of this technological replacement, the growth rate of $\hat{k}$ is the distance between **D** and **E**, rather than between **D** and **C**. This is due to the fact that the faster technological progress leads to the faster growth of effective labor, thus, slightly slower growth (recovery) rate of $\hat{k}$ than in the previous case.

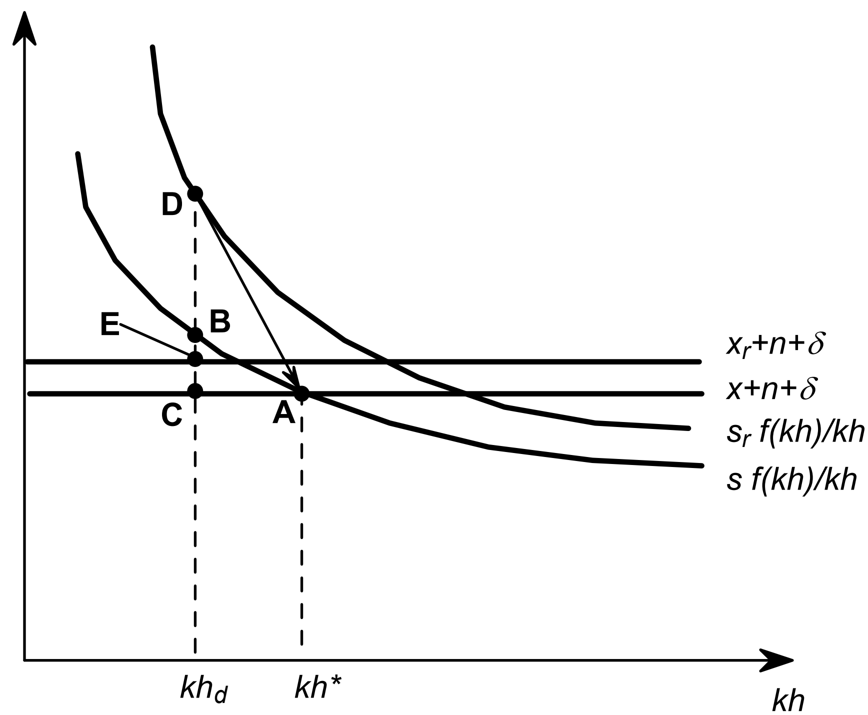

Figure 5. Transitional Dynamics with Technological Progress ($\hat{k}$ is noted as *kh*)

These analyses guide toward two policy implications. First, the rate of recovery depends on the resource allocation to the recovery activities, *i.e.* increase of saving rate. However, the increase in saving rate implies the decline in consumption level. In this context, the analysis should extend to employ the Ramsey model analysis with consumer optimization (Ramsey, 1928; Cass, 1965; and Koopmans, 1965). In this way, the optimum allocation of resources for recovery in the growth context can be studied. Secondly, the degree of mixture between old and new capital stocks in an economy can influence the recovery rate of $\hat{k}$. This implies that the technological progress during the normal circumstances become more important. For this type of investigation, the model needs to be stretched to employ the framework of endogenous growth models to compare different policies of technological progress and the impacts on disaster recovery.

5. Conclusions

The theoretical discussion and analysis of disaster is important to advance our knowledge for the impacts and consequences of a disaster, and our preparedness against disasters. While disasters are not frequently repeated phenomena and the damages from a disaster vary considerably from one disaster to another (even in the same type of disaster, such as earthquake) and from one region to another, this type of generalized analysis of theory can assist empirical analysis of disasters. For example, the effects of uncertainty after a disaster need to be incorporated in the analysis of economic impacts of the disaster, since the decision-making and response to supply and/or demand changes can be noticeably different from the ones in the pre-disaster context. In this sense, the usual assumptions of laws of supply and demand laid in the conversional models, such as Computable General Equilibrium (CGE) models, need to take into account this uncertainty and behavioral changes, discussed in Section 3. In addition, uncertainty may create sizeable influence to the production planning, especially for manufacturing sectors which decide the level of production with the anticipation of future demand stream, and may bring additional impacts on inventory management and production scheduling (Okuyama *et al.*, 2004). Further theoretical investigation of uncertainty created by a disaster will provide insights to these studies.

In addition, the theoretical analysis of disaster impacts will offer some new perspectives to the disaster related research. For example, the analysis of long-term growth with a disaster above proposed the issues of technological replacement and optimal saving rate. As in the endogenous growth theory, in the long-run, technological progress becomes the driving force of economic growth. While technological replacement or update resulted from the reconstruction of damaged capital stocks by a disaster is different from usual technological progress, in terms of its exogenous nature of shock, but is similar about the endogenous level of technology available for replacement. On the other hand, the speed of recovery depends on the extra amount of savings allocated to reconstruction activities, as shown in Section 4. However, this result extends to relate with an issue of disaster insurance, which can be considered as saving for the future. In this sense, the analysis of disaster insurance should incorporate with this type of consumption-saving optimization analysis for the long-run implications.

This paper's aim was to update the Dacy and Kunreuther's theoretical frameworks. The discussions above may have been able to reach that goal to some extent; but, it is obvious that there is still a large space to be filled and a long way to go to truly construct 'Economics of Natural Disasters'. This paper is also an invitation for the mainstream economists with theoretical orientation to disaster related research, where there are a lot of theoretical challenges left.

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