# An Analysis of Post-disaster Resources Supply and Work Environment for Restoration Planning of Facilities


**Sungjoo Hwang[1], Moonseo Park[2], Hyun-Soo Lee[3], SangHyun Lee[4]**

[1] Ph.D. Student, Dept. of Architecture and Architectural Engineering, Seoul National Univ., Gwanak_599 Gwanak-ro, Gwanak-gu, Seoul 151-742, Korea.
E-mail: nkkt14@snu.ac.kr

[2] Prof., Dept. of Architecture and Architectural Engineering, Seoul National Univ., Gwanak_599 Gwanak-ro, Gwanak-gu, Seoul 151-742, Korea.
E-mail: mspark@snu.ac.kr

[3] Prof., Dept. of Architecture and Architectural Engineering, Seoul National Univ., Gwanak_599 Gwanak-ro, Gwanak-gu, Seoul 151-742, Korea.
E-mail: hyunslee@snu.ac.kr

[4] Assistant Prof., Dept. of Civil and Environmental Engineering, Univ. of Michigan, 2350 Hayward St., Suite 2340 G.G. Brown Building, Ann Arbor, MI 48109.
E-mail: shdpm@umich.edu



**Abstract**

*Disaster event causes fatal damage on regional built environment (e.g., residential and commercial buildings, core infrastructures and roadways), which generates their functionality losses. Since economic and social activities in urban area depend on not only residential and commercial but also public services provided by facilities and infrastructures, it is essential to implement appropriate restoration planning for recovering functions of facilities within a limited time. In this regard, regional recovery environment (e.g., resource supply chain, debris disposal system, and transportation network) after disaster can have negative impacts on reconstruction operations of individual facility compared to a pre-disaster situation. This research thus develops a system dynamics (SD) model to understand the effects of a recovery environment (e.g., required resource and service availability, and their effects on restoration work efficiency) on restoration efforts of facilities in a post-disaster situation. The results of simulation showed that a better understanding of a recovery environment for individual facility restoration can support project managers to implement more appropriate restoration planning to rapidly recover facility's functionality with reduced wastes of time, cost and resources. This model also has a potential to be utilized for implementing more effective restoration plans for facilities and infrastructures in region with an understanding of regional recovery environment.*



**Keywords**: Disaster, Recovery, Reconstruction, Resource Allocation, Facility Management


**Body of Paper**


Introduction
Previous Research
Model Development
Model Behavior Test
Conclusions
References

## Introduction

Disasters such as flood, hurricanes, and earthquake cause fatal damage on regional built environment including residential and commercial facilities, as well as core infrastructures. It generates an unusually large and immediate loss of public and capital services (Olshansky et al. 2012). Since economic and social activities in urban area depend on not only residential and commercial but also public services produced by the operations of core infrastructures (e.g., electric power, water and gas supply systems, communication networks, rescue center, and transportation system) (Shoji and Toyota 2009), it is essential to implement immediate and appropriate restoration planning for recovering function of facilities within a limited time.

Due to the need for rapid restoration of built environment in the aftermath of disasters, there are a great deal of efforts to optimize repair and reconstruction process with a management tools, system, and/or technologies that have been developed for the purpose of reducing construction duration and cost, as well as effectively allocating utilizing construction resources (AbouRizk 2011; Pena-Mora et al. 2012). Despite these efforts, they have been generally conducted base on the assumption that building projects (including repair and reconstruction) are performed in the normal construction environment where external negative impacts from recovery environment can be ignored (i.e., normal operation on public service and resource supply systems). In an emergent situation in the aftermath of a disastrous event, however, some restrictions exist for applying these construction methods in the current body of research: (a) the availability of resources, such as materials, equipment, and construction workforces is generally expected to be limited because of the high demand for recovery of facilities and infrastructures at the same time (Pachakis and Kiremidjian 2004; Orabi et al. 2009); (b) debris-generating events lead to lack of available spaces for recovery efforts, in turn, requires lengthy debris removal and disposal operations (Shen et al. 2004; Olshansky et al. 2012); (c) the delivery of recovery resources and disposed debris is delayed due to damaged pathways and/or transportation system (Holguin-Veras et al. 2007); and (d) restoration priority among a different types of facilities and infrastructures affects resource availability for a construction of a certain individual facility due to associated interdependency among facilities, and the differences in relative importance of services that each facility provides (Shoji and Toyota 2009). These recovery conditions after disaster can have negative impacts on reconstruction operations of individual facility compared to a pre-disaster situation. Despite the need for understanding the recovery environment, there exists difficulties in analyzing complex, interdependent and dynamic (i.e., changes over time) recovery process among numerous types of facilities/infrastructures.

Therefore, in the post-disaster recovery environment, dynamic features of the recovery environment at a regional-level (e.g., resource supply chain, debris disposal system, transportation network, and interdependency among facilities) needs to be analyzed from a holistic perspective. This research thus develops a system dynamics (SD) model to understand the effects of a recovery environment (e.g., resource availability, required service availability, and their effects on restoration work conditions) on restoration efforts of facilities in a post-disaster situation. The main focus of this research is the resource supply and work environment for individual facility restoration process that is affected by regional-level interdependent recovery operations among different type of facilities within limited resources after disaster. A better understanding of the recovery environment can help to more effectively implement construction planning, deploy and utilize limited resources in order to minimize both the performance loss of the damaged built environment and the reconstruction costs with an awareness of available resources and working conditions at a certain time (Orabi 2009).

## Previous Research

### *Response and Recovery Efforts in Disaster Situation*

Both natural disasters (e.g., floods, earthquake, hurricanes, and so forth) and man-made disasters (e.g., terror, explosion or detonation, and so forth) severely cause damage in a region (Hu et al. 2004). Effective disaster response and recovery planning can not only alleviate damage but also help recover both inconvenient and impoverished daily life of population and interrupted operation of facilities to their pre-disaster conditions. In this regard, many research efforts have been conducted on overall disaster management cycle, including disaster preparedness, emergency responses, recovery and emergent operation. This body of research includes damage prediction and simulation (Pinelli et al. 2004), evacuation planning (Dimakis et al. 2010; Chu et al. 2012), rescue planning (Yotsukura and Takahashi 2009), recovery planning (Shoji and Toyota 2009; Pachakis and Kiremidjian 2003), and technologies for disaster mitigation and/or assessment (Pena-Mora et al. 2012).

In particular, many researchers on disaster management have paid attention on reconstruction process and recovery of facilities' functionality at both regional- and project- level with a focuses on a resource supply chain management (Le Masurier et al. 2006; Orabi et al. 2010), debris disposal management (Swan 2000; Shen et al. 2004), and preparing and planning to the impact of disasters on civil infrastructure (Chen and Tzeng 1999; El-Anwar et al. 2009; Orabi et al. 2009). This is because the restoration of damaged civil infrastructure systems needs to be carefully planned in order to alleviate the impact of disasters on local communities (Karlaftis et al. 2007). Due to its importance on local area, this research focuses on functional requirements of facilities and their restoration in recovery stages.

On the other hand, the restoration activities involves repairing and rebuilding houses, commercial buildings, pathways, critical infrastructures and facilities to provide populations in a regions with normal residential, commercial, transportation, and public services (Olshansky et al. 2012). Due to complexity of restoration operations and interdependency among facilities, traditional approaches are limited in their ability to analyze multiple interdependent processes operating simultaneously. In this regard, computer simulation techniques can articulate the complex behavior of interest over time. In other word, simulation approaches partially overcome the empirical problem of data availability, especially in emergent post-event situation, because of its some advantages including the ability to precisely track the behavioral steps and feedback process leading to the outcomes of interest (Harrison et al. 2007).

### *Reconstruction Process in Normal and Emergency Situation*

In previous research aimed to analyzing construction process and operation, the resource logistics and schedule performance with a detailed event-oriented view are the main interest (Pena-Mora et al. 2008). The main issues hear are how to optimize construction process to reduce construction cost and duration within assigned resources, with a focuses on an individual facility or a project level. This research includes resource allocation issues using advanced scheduling and optimization methods, and/or simulation approach with a detailed level of view, such as genetic algorithm and discrete event simulation (Hegazy 1999; El-Rayes and Moselhi 2001; Ibbs and Nguyen 2007). This is due to their advantages in describing process and operational details including resources by its powerful ability to handle complexity and uncertainty (Law and Kelton 2006).

In disaster situation, however, most severely restricted aspect of the restoration activities was its inefficient relief effort and resource supply that did not deliver in a timely fashion the critical supplies needed at the disaster site or region (Holguín-Veras et al. 2007). An understanding of a recovery environment can be helpful for implementing more reliable restoration plans in a regional post-disaster emergent situation. In this regard, an SD simulation model provides an analytic solution for complex, nonlinear, and dynamic systems by focusing on interactions among variables and understanding their structures (Sterman 2000; Williams 2002; Harrison et al. 2007). While existing construction operation analysis methods that are widely used in the fields of construction and civil engineering have focuses on detailed description of process, SD modeling in macro-level (or at a regional-level in this research) has more strength on understanding dynamic changes in regional-level recovery environment and analyzing the effects of a recovery environment on restoration activities. Analysis results of SD model thus can provide facility reconstruction planners (or methods) with more information on a recovery environment in post-disaster situation, which is helpful for making emergent recovery plans for facilities.

### *The Effects of Post-disaster Recovery Environment on Restoration*

According to Holguin-Veras and Jaller (2007), the problems in resource supply and logistics system due to damaged infrastructure and facilities are critical aspects to implement recovery plans at a disaster region. These include the excessive needs after disaster, their temporal evolution, complex interactions among the dozens of supply chains, timing and types of commodities requested, their relative importance to utilize. Also debris-generating events cause the problems in restoration work conditions caused by shortage of spaces for resource delivery and storage, and performing construction work (Chua et al. 2010). Since these are generated in resource supply system and working environment to receive, store, ship, deliver, manage, or utilize commodities, personnel, equipment, or any other type of service at times of disaster (Holguin-Veras and Jaller 2012), the following aspects need to be considered in facility restoration.

(1) The availability of resources

In the aftermath of disasters the resources available to perform reconstruction and recovery for facilities are limited because other residential, commercial facilities and core infrastructures in disaster region also requires rapid recovery of their functionality. Not only reconstruction of facilities but also rescue efforts and disposal operation of debris from damaged structures requires materials, personnel, equipment, or any other public services (e.g., electric power, gas, water, communication networks, transportation capability, emergency rescue capability, and administrative services) as well. This causes excessive needs for resources or other services in a disaster region. In this situation, in particular, the functionality loss of core infrastructure from damage can reduce pubic services supply, in turn, exacerbate the availability required services for restoration work.

(2) The need for excessive debris disposal

In post-disaster situation, debris disposal capability can be overwhelmed from excessive debris from damage of built environment (Swan 2000). It causes delays in deployment and delivery of resources and supply of public services, and the lack of transportation capabilities. It may also obstruct reconstruction activities the lack of space because building construction requires space to move, store, and fabricate materials, and to perform work (Riley and Sanvido 1995). Due to the importance of spaces in construction operation, previous research has considered space as a kind of construction resources and has subsequently incorporated it as an integral part of planning constraints (Zouein and Tommelein 2001; Chua et al. 2010). Debris clearance, removal, and disposal efforts thus need to be planned and coordinated prior to other reconstruction activities to alleviate the lack of working space and pathways for recovery efforts.

(3) The loss of transportation capability

The damage in roadways, bridges, and railroad may result in the functionality losses of transportation system. As a result, the resource supply and debris disposal system may be severely damaged due to delays in delivery (Holguin-Veras and Jaller 2012). Recovery of transportation capability is critical issues for not only reconstruction and recovery process but also precedent emergency response stages including egress or rescue activities.

(4) Restoration priority

According to Shoji and Toyota (2009), interdependency among facilities should be considered to improve the efficiency of the restoration process in regional-level built environment. For example, the recovery and the normal operation of commercial facilities requires public services such as electric power and water offered by normal operation of power plants, water supply systems and so forth. In this situation the restoration of critical facilities and infrastructures that offers core public services may have a high priority for recovering their functions. The relative importance and restoration priority among facilities is due to many factors, such as needs for services facilities provide, political issues, public opinion, and system relationships (Kovel 2000). In the context of the lack of resources available, the recovery priority of each facility in a region need to be considered to implement proper reconstruction plans for corresponding facilities. For instance, in a reconstruction project of general commercial building project managers need to set a proper project start time and scheduling by considering available resources that can be assigned when other damaged critical infrastructure in a region requires recovery of functionality and resource allocation by priority.

To sum up, Fig. 1 describes the differences between normal and post-disaster reconstruction operation with an understanding of significant constraints when events occurs.

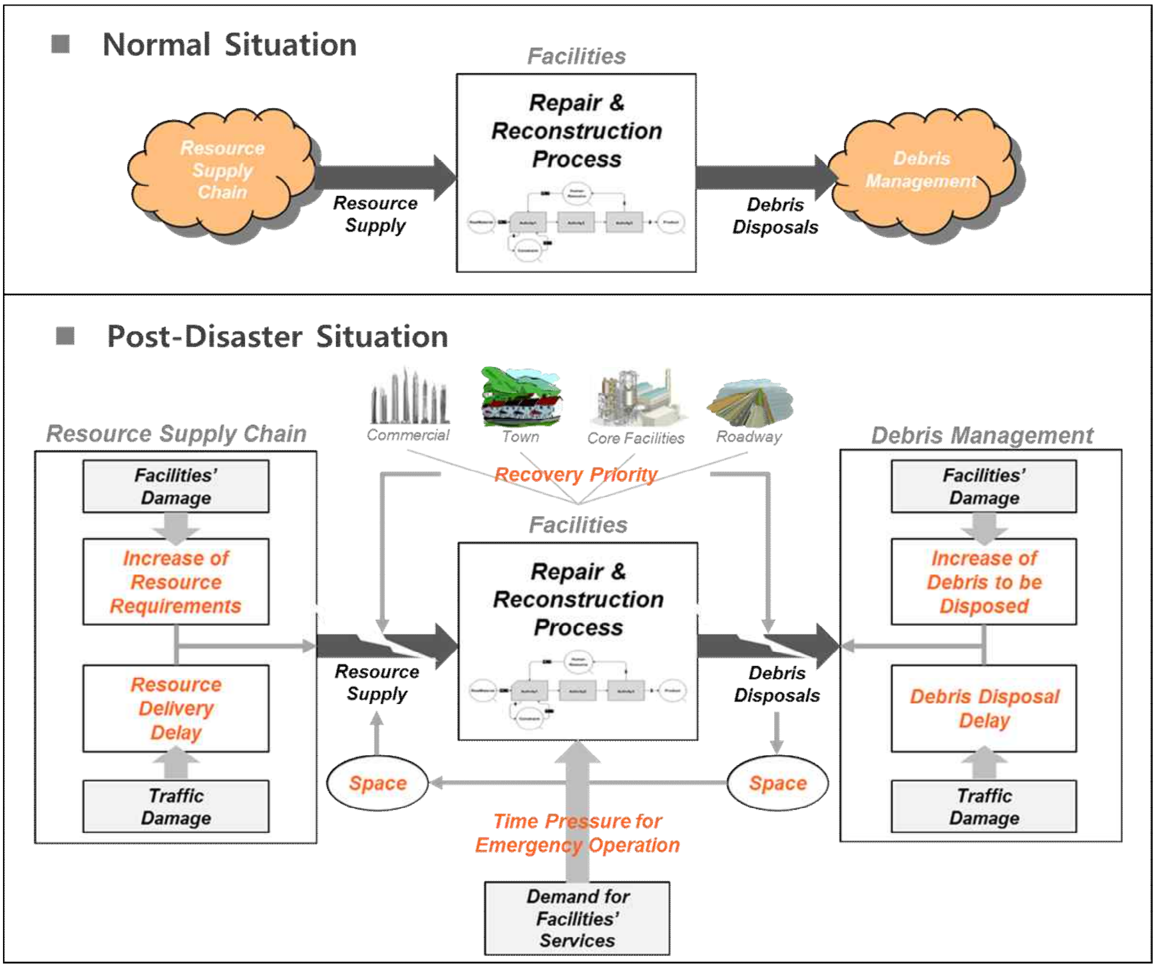


**Fig. 1** Post-disaster Reconstruction Operation Compared to a Normal Situation

## Model Development

### *Model Framework*

This research constructs an SD model based on investigated effects of recovery environment on facility restoration efforts in disaster situation. The model framework, as described in Fig.2, shows (a) the recovery environment at a regional-level, and (b) its impact on the restoration operation of an individual facility.

At a regional-level, the disaster-event generates considerable needs for recovery of built environment, which requires excessive restoration resources. To assess damage on facilities/infrastructures and demand for resources, two types of information need to be utilized: (a) disaster information including physical intensity of event, location of disaster sources (i.e., epicenter), and spatial extent of damage; and (b) regional facility information that includes physical scale of facilities, number of facilities, and the density of built environment.

These factors affect the internal process of resource distribution and utilization for interdependent restoration operations among damaged facilities and their recovery of functionality. Although there are great number of types of facilities in region, they can be categorized into three types according to their functions and services they provide: (a) critical facilities and/or infrastructures that provides core public services such as electric power, gas, water, communication abilities, rescue resources; (b) general facilities such as residential and commercial buildings, and (c) transportation infrastructures such as roadway, railroad, and bridges that provide transportation services (Song et al. 1995; Shoji and Toyota 2009)

On the other hand, excessive debris generation from disaster events can affect the supply of intangible resources such as spaces for restoration work, and transportation capability for resource logistics. As a result, recovery process after disaster in region includes: (a) restoration of critical facilities, (c) restoration of residential and commercial facilities; (c) restoration of transportation infrastructures, and (d) debris disposal operations. Within limited resources, resource distribution among different recovery operations above can be mostly determined by the recovery plans, with a consideration of the relative importance and interdependency among functions and services that each recovery efforts can recover.

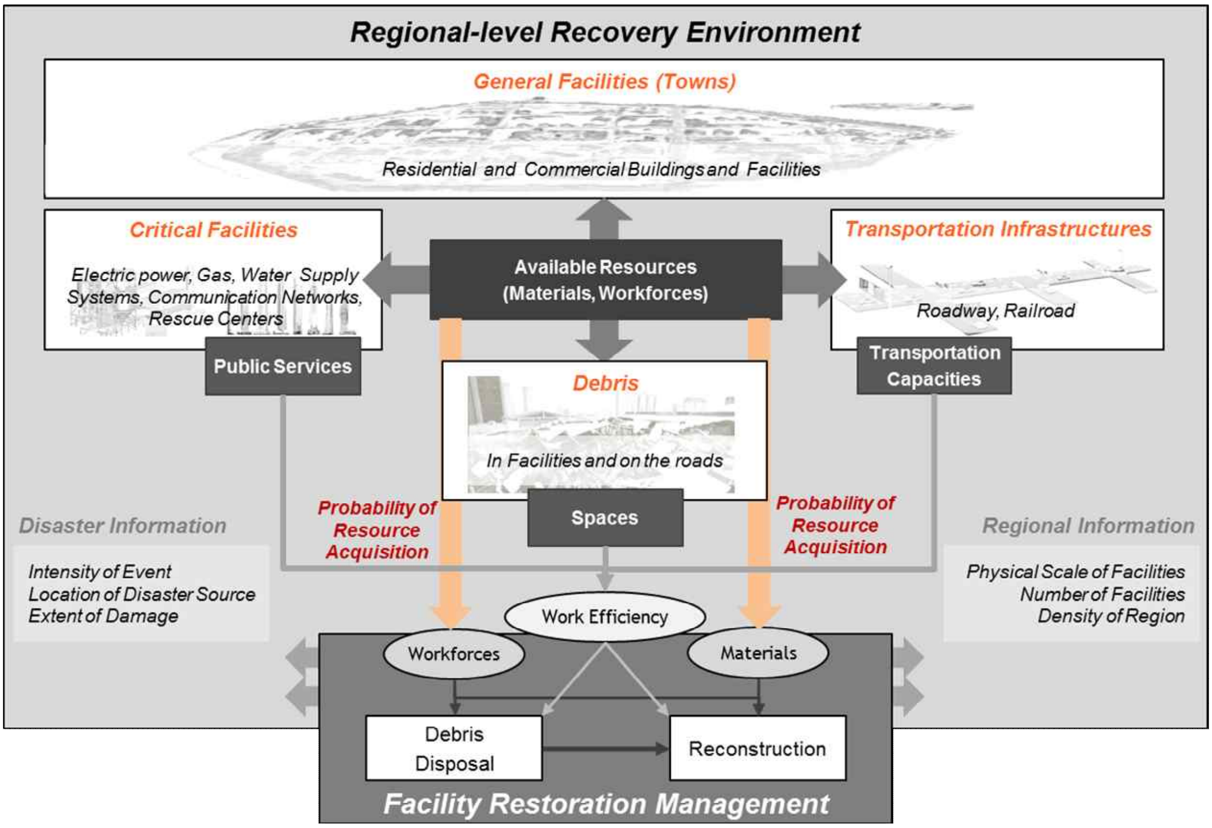


**Fig. 2** Model Framework

At an individual facility level, dynamic changes in regional-level recovery environment can have significant effects (generally negative impacts) on a restoration operation of a certain type of facility. This is especially due to reduced resource availability (e.g., construction materials and workforces) for restoration, and changes in restoration working environment determined by the reduced availability of public services for construction work, work spaces, and surrounding transportation capabilities for resource supply.

As a result, regional-level recovery interdependencies among facilities and the recovery planning such as set of decision on prioritization of recovery projects can affect the planning of certain type of individual facility in accordance with the probability of resource acquisition (affected by resource availability in region) and the expected work efficiency (caused by changes in restoration working environment) (Orabi 2010). This research thus develops both a model for regional-level recovery environment and a model for individual facility-level restoration operations.

### *Regional-level Damage and Recovery of Built Environment*

(1) Damage of facilities

Fig.3 shows the model for damage generation and recovery processes of regional built environment. At first, the damage of facilities is determined by the function of the physical scale of facilities (Eq. 1), and the function of the degree of damage intensity on facilities (Eq. 2):

$$V_{j\cdot tot} = f(r_j, \rho_j, V_j) \qquad (1)$$

$$I_{j\cdot tot} = f(r_j, I_0) \qquad (2)$$

where $V_{j\cdot tot}$ = total physical scale of a j-type facilities in region (j = critical facilities (c), general facilities (g), and transportation infrastructure (p)), $r_j$ = distance of a j-type facility from a disaster source, $\rho_j$ = density of j-type facilities in region, $V_j$ = physical scale of each j-type facility, $I_{j\cdot tot}$ = the damage intensity on j-type facilities in region and $I_0$ = intensity of disaster event on the point of disaster source.

In the real world, the disaster intensity function $(I)$ and regional density function $(\rho)$ is so complex that they need to be analyzed from disaster simulators and/or geographical and geological information to contain complex effects of various events (Koto and Takeuchi 2003). Since a focus of this research is dynamic features of recovery environment in region, the model is developed based on the assumption that the disaster intensity is simple linear function and the regional density is uniform, as follows:

$$I(r) = I_0(1 - \frac{r}{d_{\max}}) \qquad (3)$$

$$D_{c\cdot tot} = \int_0^{d_{\max}} 2\frac{n_c}{(d_{\max})^2} \cdot \overline{V_c} \cdot r \cdot I_0(1 - \frac{r}{d_{\max}})dr \qquad (4)$$

$$D_{g\cdot tot} = \int_0^{d_{\max}} 2\frac{n_g}{(d_{\max})^2} \cdot \overline{V_g} \cdot r \cdot I_0(1 - \frac{r}{d_{\max}})dr \qquad (5)$$

$$D_{p\cdot tot} = \int_0^{d_{\max}} 2\frac{\tau \cdot A_E}{(d_{\max})^2} \cdot \overline{V_p} \cdot r \cdot I_0 (1 - \frac{r}{d_{\max}}) \cdot dr \qquad (6)$$

where $r =$ distance of damaged region from disaster source, $D_{j\cdot tot} =$ total damage of j-type facilities and infrastructures in disaster region, $n_c =$ total number of critical facilities in disaster region, $d_{\max}$ = maximum distance of damaged region from disaster source, $\overline{V_c} =$ average volume of each critical facility in disaster region, $n_g =$ total number of general facilities in disaster region, $\overline{V_g} =$ average volume of each general facility in disaster region, $\tau =$ the ratio of total area of pathway in disaster region, $A_E =$ total damaged area from disaster event, and $\overline{V_p} =$ average volume of pathway per unit area in disaster region.

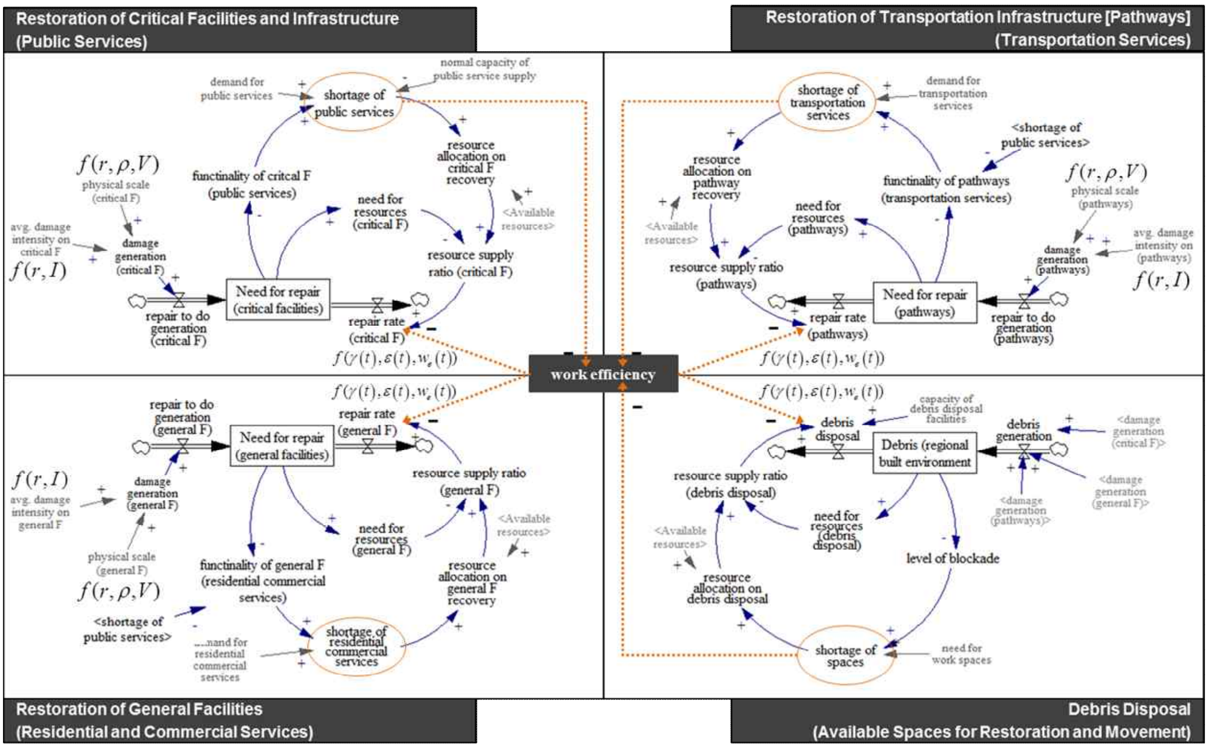


**Fig. 3** Damage of Built Environment and Interdependent Recovery Process

(2) The functionality of facilities

The damaged facilities and infrastructures may lose their functionality after disaster, in turn, causes the shortage of services they can provide in region due to interrupted operations of facilities. When the critical infrastructures in region are severely damaged, the lack of public services for operating any other facilities can also causes the losses of diverse facilities' normal function. In the model the functionality of facilities and the regional shortage of services are calculated by the following equations:

$$S_j(t) = MAX\left[\frac{(N_j(t) - c_j \cdot F_j(t))}{c_j \cdot F_j(t)}, 0\right] \quad (7)$$

$$F_j(t) = MIN\left[1 - \frac{W_j(t)}{D_{j \cdot \max}}, 1 - S_c(t)\right] \quad (8)$$

where $S_j(t)$ = shortage level (0-1) of services j-type facility provide at time (t) (j = public services by critical facilities (c), residential and commercial services by general facilities (g), and transportation services by transportation facilities (p)), $c_j$ = capacity of services offered by j-type facilities in region, $N_j(t)$ = total demand (need) for j-type services at time (t) in region, $F_j(t)$ = functionality level of j-type facilities at time (t) in region (0-1), $W_j(t)$ = required work for restoration of damaged j-type facilities at time (t) in region, $D_{j \cdot \max}(t)$ = maximum damage of j-type facilities at time (t), $S_c(t)$ = shortage level (0-1) of public services for operating j-type facilities at time (t) in region.

(3) The restoration of facilities

The restoration of facilities needs to be done within a limited time to rapidly supply required services (i.e., public, residential, commercial, and transportation services) for economic and social activities in region. Although the restoration planning is well-implemented, the loss of capabilities of supplying construction resources and required services can interrupt the facility restoration. Due to sudden increases of demand for resources and the lack of capability of required services for reconstruction work in disaster region, reconstruction work rates in emergent situation are generally delayed compared to pre-disaster condition (i.e., normal situation). Work efficiency that affects work repair/reconstruction work rates is determined by the function of available work spaces, public services and transportation services for conducting restoration work (Riley and Sanvido 1995; and Shoji and Toyota 2009). In the model the work progress rate of restoration process is determined by following equations:

$$w_{a \cdot j}(t) = \gamma_j(t) \cdot \varepsilon(t) \cdot w_{e \cdot j}(t) \quad (9)$$

$$\varepsilon(t) = f\left(S_c(t), S_p(t), S_d(t)\right) \quad (10)$$

$$\gamma_j(t) = MIN\left[1, \frac{Rd_{m \cdot j}(t)}{Rn_{m \cdot j}(t)}, \frac{Rd_{w \cdot j}(t)}{Rn_{w \cdot j}(t)}\right] \quad (11)$$

where $w_{a \cdot j}(t)$ = actual restoration work rate of damaged j-type facilities at time (t), $w_{e \cdot j}(t)$ = expected restoration work rate (optimistic) of damaged j-type facilities at time (t), $\varepsilon(t)$ = work efficiency (0-1)for restoration work at time (t), $\gamma_j(t)$ = resource supply ratio (0-1) for restoration of damaged j-type facilities at time (t), $S_c(t)$ = shortage level (0-1) of public services for restoration work at time (t), $S_p(t)$ = shortage level (0-1) of transportation services for resource supply at time (t), $S_d(t)$ = shortage level (0-1) of spaces for restoration work at time (t), $Rd_{m\cdot j}(t)$ = distributed materials for restoration of j-type facilities at time (t), $Rd_{w\cdot j}(t)$ = distributed workforces for restoration of j-type facilities at time (t), $Rn_{m\cdot j}(t)$ = needs for materials for restoration of j-type facilities at time (t), and $Rn_{w\cdot j}(t)$ = needs for workforces for restoration of j-type facilities at time (t).

***Resource Allocation***

In disaster region, there is a wide range of area where the restoration of facilities and infrastructures is required due to shortage of the functionality of built environment. To minimize the losses of economic and social activities, the resource allocation planning among facilities needs to be implemented by considering to what extent the shortage of a certain type of services are generated and how rapidly a certain type of services is required. For example, when a power plant that can provide electric power is severely damaged, they have a high recovery priority due to an extreme shortage of electric power in region. When a wide range of residential area is damaged, the recovery priority of houses may depend on the availability of temporary housing. In addition, debris disposal in disaster region needs to be done by priority to avoid disturbance of resource movement, reconstruction work and so forth. As a result, plans for resource distribution to different types of recovery efforts is implemented based on the relative shortage among different types of services (public, residential, commercial, and transportation services), and relative time pressure on recovery.

(1) Distribution of construction workforces

Since construction workforces is non-consumable resources, resource distribution process is twofold: 1) the distribution of newly supplied workforces (e.g., relief efforts); and 2) the adjustment of existing workforces who had been already allocated to different restoration projects (Orabi 2010) (see Fig. 4). After a disaster event, the resource distribution process is continuously adjusted with dynamic changes in shortage of services according to progress of recovery works on critical facilities, general facilities, transportation infrastructures, and debris disposal works. The time pressure on rapid supply of services that can be recovered by each recovery effort (determined by relative importance of services, and managerial policy factor) also affect resource distribution process, as following equations:

$$\delta_{w\cdot j}(t) = \frac{S_j(t)/T_j}{(S_c(t)/T_c + S_g(t)/T_g + S_p(t)/T_p + S_d(t)/T_d)} \quad (11)$$

$$Rd_{w\cdot j}(t+1) = \int_0^t \frac{\delta_{w\cdot j}(x+1)\cdot Ra_{w\cdot tot}(x+1)}{t_d} + \frac{Rd_{w\cdot tot}(x)}{t_a}\cdot\left\{\delta_{w\cdot j}(x+1) - \left(\frac{Rd_{w\cdot j}(x)}{Rd_{w\cdot tot}(x)}\right)\right\}dx \quad (12)$$

where $Ra_{w\cdot tot}(t)$ = total available workforces in region at time (t), $Rd_{w\cdot j}(t)$ = distributed workforces for restoration of j-type recovery works (j = critical facilities (c), general facilities (g), transportation infrastructures (p), and debris disposal (d)) at time (t), $T_j$ = time pressure level (1-0) for recovery of j-type recovery work, $\delta_{w\cdot j}(t)$ = workforce distribution ratio (0-1) for j-type recovery works, $t_d$ = time for resource distribution, $t_a$ = time for resource adjustment.

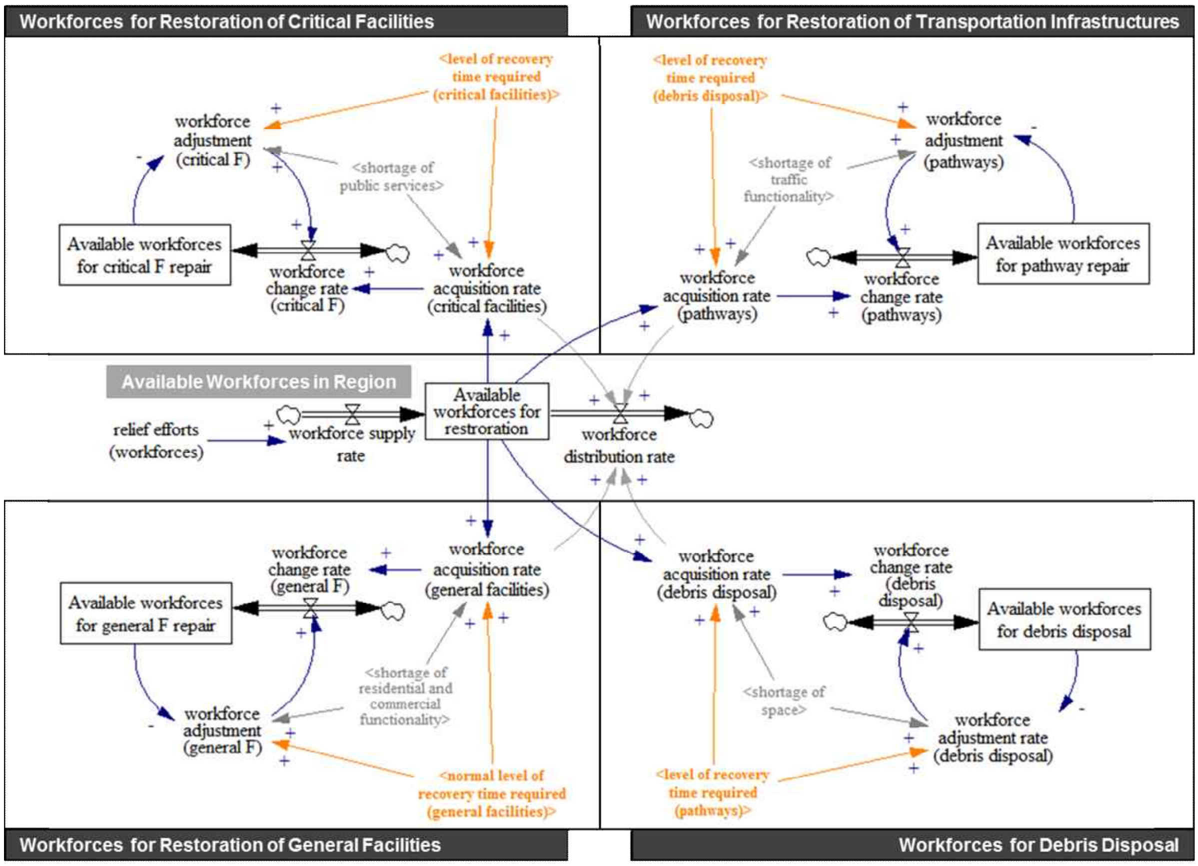


**Fig. 4** Resource Distribution Process (Workforces)

(2) Distribution of construction materials

Fig. 5 shows the material distribution process for restoration works that will be performed at different types of facilities and infrastructures. Compared to distribution process of workforces, material distribution process only includes the deployment of newly supplied materials because they are consumable resources and thus cannot be reused. The material distribution process in the model is determined by the following equations:

$$\delta_{m\cdot j}(t) = \frac{S_j(t)/T_j}{(S_c(t)/T_c + S_g(t)/T_g + S_p(t)/T_p)} \qquad (13)$$

$$Rd_{m\cdot j}\left(t\right)=\int_0^t \frac{\delta_{m\cdot j}\left(x\right)\cdot Ra_{m\cdot tot}\left(x\right)}{t_d}dx \qquad (14)$$

where $Ra_{m\cdot tot}\left(t\right)$ = total available materials in region at time (t), $Rd_{m\cdot j}\left(t\right)$ = distributed materials for restoration of j-type recovery work ( j = critical facilities (c), general facilities (g), and transportation infrastructures (p)) at time (t), $T_j$ = time pressure level (1-0) for recovery of j-type recovery work, $\delta_{m\cdot j}\left(t\right)$ = material distribution ratio (0-1) for j type recovery work.

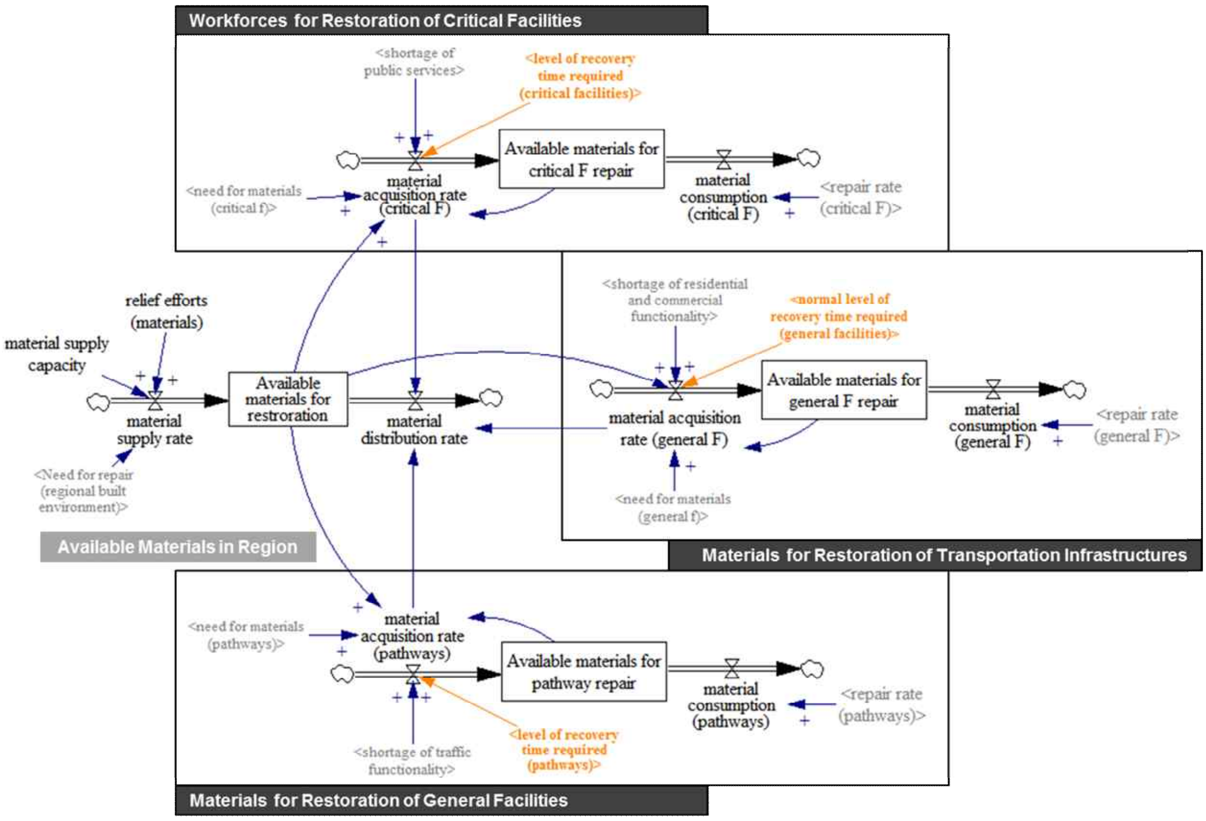


**Fig. 5** Resource Distribution Process (Materials)

### *Individual Facility-level Restoration Operations*

To analyze the effects of regional-level recovery environment on each facility restoration process, this research construct a sub-model describing facility restoration operations. Based on the effects of a recovery environment (e.g., resource availability, available public service, work space and transportation capability) on facility restoration operations analyzed from a regional-level model, facility managers can analyze the restoration process of an own facility as well as implement the appropriate managerial action such project start time and scheduling, by using the model as shown in Fig 6.

In the facility restoration process model, damage of facility is determined by its physical scale, and the degree of damage intensity according to its location. The amount of debris generation affects the changes in available space to move, store, and fabricate materials, and to perform work according to the locational information such as density of surrounding area and the occupied area of a facility (Riley and Sanvido 1995).

Restoration project durations of a facility can extend or shrink based on the number and availability of the resources assigned to each activity. Restoration work rate is also affected by the work efficiency resulted from the availability of spaces and/or required services (Orabi 2010). For instance, there are significant shortages in public and transportation services provided by critical facilities and infrastructures, a restoration project of commercial building (which is a part of general facility type) may have a lower recovery and resource allocation priority relatively within a limited resource. Furthermore, numerous restoration projects for residential and commercial facilities in a severely damaged region have to compete to acquire restoration resources. Among the same types of facilities, the probability of resource acquisition can be decided by the numerous factors, including (not being limited to) the importance of the facilities, the number of competitors, and the amount of regional resource needs.

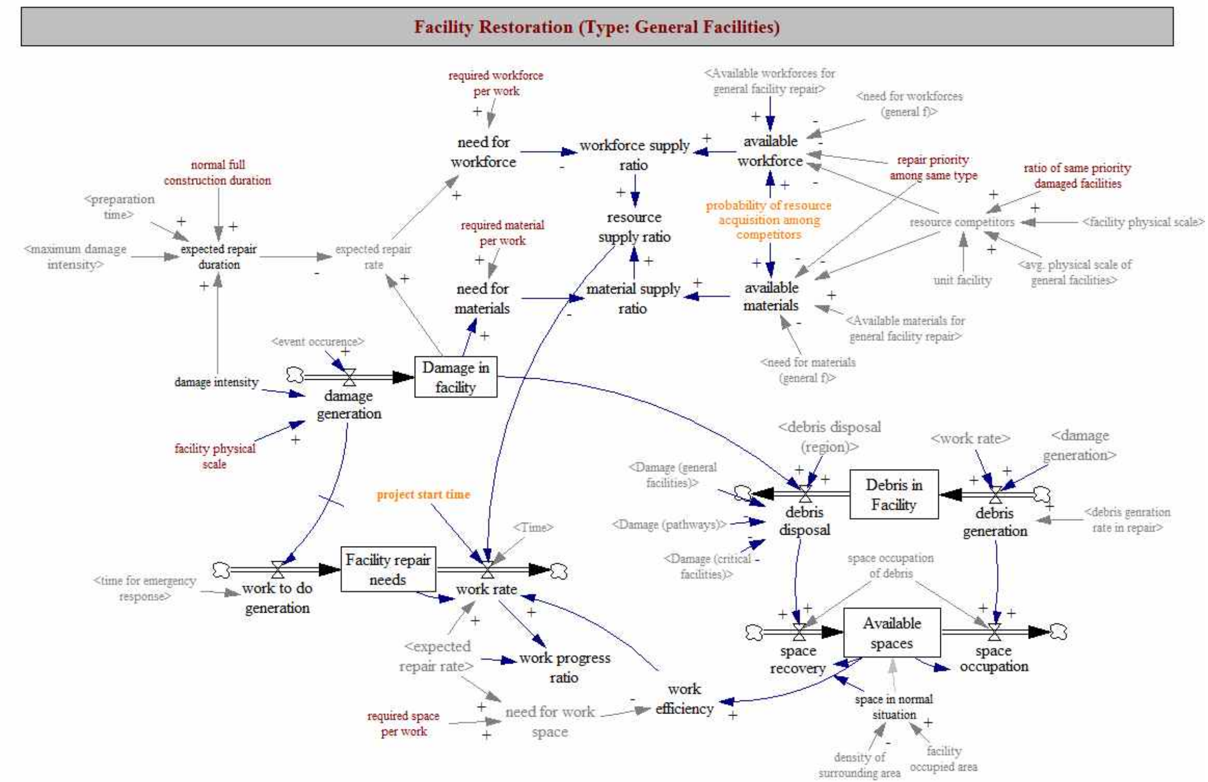


**Fig. 6** Facility Restoration Process

## Model Behavior Test

Based on developed model presented above, this research conducts model behavior tests to analyze the effects of a recovery environment on restoration of facilities in disaster situation. This model may have limitations on accurately reflecting reality because the effects of disaster on region in the real world are generally very complex. The recovery effort is also complicated because they includes not only restoration of facilities and infrastructures but also emergency response activities such as (not being limited to) evacuation, rescue, loss control, and risk financing (Pradhan et al. 2007). The model thus should encompass accurate damage assessment from more detailed disaster, and geographical and geological information, as well as the effects of other types of recovery efforts on facility restoration operations. However, it can be still useful for conducting comparative analysis among diverse managerial decisions for facility restoration (e.g., setting recovery priority among different facility types and restoration project scheduling), with an understanding of interdependent recovery process in region as well as the effects of recovery environment for facility restoration.

The behavior test in this research include: 1) an analysis of the changes in regional recovery environment according to diverse managerial policies and/or recovery plans that set the recovery priority among different types of facility; and 2) an analysis of the effects of regional post-disaster recovery environment on restoration operation of an individual facility with a focus on the availability of resources and related services for restoration work, and the working conditions. The test is conducted based on the disaster scenario from actual damage in south-east region of Korea caused by the typhoon Maemi in September 2003. Detailed disaster and regional information of this scenario is described on Table 1.

**Table 1** Disaster Scenario (NDMI 2013; Statistics Korea 2013)

| Variables | Value | Unit |
|---|---|---|
| Average physical scale of critical facilities in region | 2800 | $m^3$/EA |
| Average physical scale of general facilities in region | 1600 | $m^3$/EA |
| Average physical scale of pathways in region | 49 | $m^3$/m |
| Number of critical facilities in region | 295,471 | EA |
| Number of general facilities in region | 1,515,374 | EA |
| Pathway density in region | 0.00106 | m/$m^2$ |
| Spatial extent of damage | 500000 | M |
| Damaged Facilities | 4804 | EA |
| Damaged Pathways | 422,476 | m |

### *The Effects of Managerial Policy on Regional-level Recovery Environment*

Table 2 describes three scenarios for diverse regional-level managerial policies of setting the recovery priority among different types of facilities including: (a) the first case without any recovery prioritization that all recovery efforts in region have to compete for limited resources, which is a base case (Graph 1 in Fig. 7-8); (b) the second case of setting the recovery priority on restoring critical facilities and debris disposal efforts (Graph 2 in Fig. 7-8); and (c) the third case of setting the recovery priority on restoring critical facilities and debris disposal efforts, as well as n restoring transportation infrastructure (Graph 3 in Fig. 7-8).

**Table 2** Model Test Scenario: Managerial Policy of Setting Recovery Priority

| | Description of Managerial Policy | The Level of Time Required for Recovery | | | |
|---|---|---|---|---|---|
| | | Critical Facilities | General Facilities | Transport Infra. | Debris Disposal |
| **Graph 1** *Base Case* | No policy of setting recovery priority (All project compete for limited resources) | 1 | 1 | 1 | 1 |
| **Graph 2** | Setting recovery priority on restoring critical facilities and debris disposal efforts | 0.2 | 1 | 1 | 0.2 |
| **Graph 3** | Setting recovery priority on restoring critical facilities and debris disposal efforts, as well as restoring transportation. | 0.2 | 1 | 0.5 | 0.2 |

As shown in Fig. 7 which displays simulation results of recovery work progress rates at regional-level, the high priority to restoration of critical facilities and debris disposal efforts results in rapid recovery to normal situation. (i.e., Graph 2 compared to Graph 1 in Fig. 7). This is because the importance of recovery of spaces and public service supply capability on restoration process. In other word, the shortage of spaces and public services can result in delays in overall restoration efforts which require sufficient spaces for resource supply and work performance and public services such as electric power and water even though there are enough resources for facility restoration.

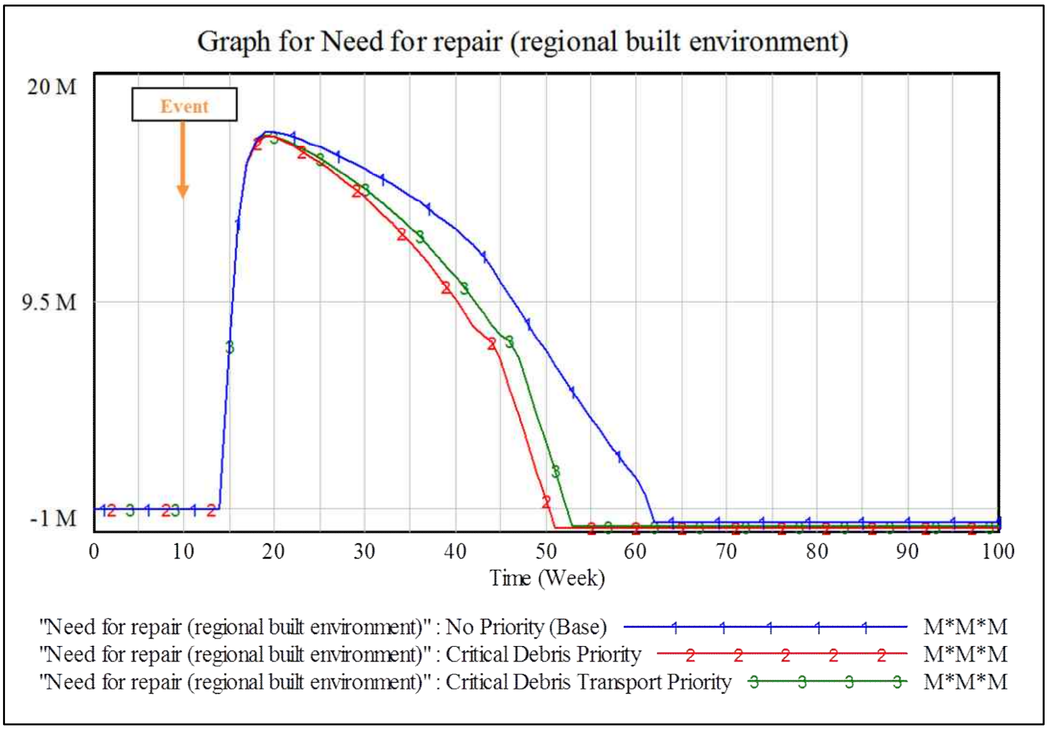


**Fig. 7** Facility Restoration Process

The resource availability for restoration of an individual facility can be changed according to regional-level recovery planning. Fig. 8 shows an example of resource availability on regional restoration projects for general facilities. When a great number of facility restoration projects have to equally compete for limited resources without any recovery prioritization plans (Graph 1 in Fig. 8), restoration projects for general facilities (e.g., normal residential or commercial buildings) have more chances to acquire enough resources for restoration at an earlier time. On the other hand, it requires more time for general facilities to acquire restoration resources when regional recovery efforts have more focuses on critical facility restoration and/or debris disposal at an early time (Graph 2 in Fig. 8).

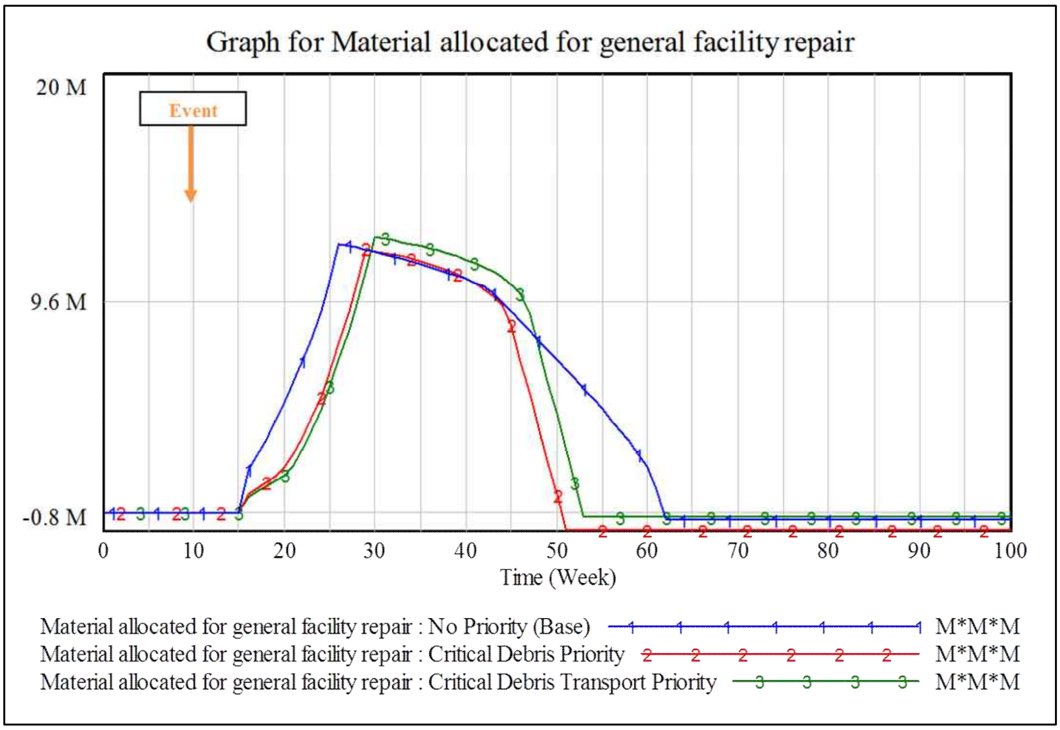


**Fig. 8** Resource Availability on Restoration Projects for General Facilities

### *The Effects of Regional Recovery Environment on Restoration of Each Facility*

Based on resource availability in region analyzed above, this research analyzes the effects of regional recovery environment on an individual facility restoration project. This behavior test is based on the following assumption: (a) the one of general facility requires restoration of its damaged structure to recover its functionality; (b) a project manager of this facility may compete for restoration resources with other competitors (i.e., other restoration projects of residential and commercial building); (c) available resources in region may be limited because restoration of critical facilities and debris disposal efforts need to be concerned by priority; and (d) a project manager needs to implement appropriate project scheduling (e.g., project start time) with a consideration of available resources and other constraints.

Fig. 9 shows the probability of resource acquisition for an individual facility restoration project when the chance for resource allocation among competitors (i.e., other same types of restoration projects such as residential and commercial building restoration) shows the random uniform function. Although simulation is performed on the assumption that disaster affects the regional built environment at the 10th week, this restoration project can be commenced almost 30-40 weeks later due to uncertainty of resource allocation. The restoration process can be thus completed 50-60 weeks later after a disaster event (See Fig. 10). The recovery of damaged facilities and infrastructures by the typhoon Maemi in Korea actually took one year or more, which was delayed for about one or two months more than expected because of problems in resource supply and impeditive working conditions.

From the results of the behavior test, as shown above, it is confirmed that model can provide reliable simulation results of how regional recovery environment is affected by recovery plans and to what extent the regional recovery environment can have an impact on individual facility restoration operations. The behavior test this research conducts will be continuously and diversely conducted in the future research in order to modify and complement the model, which can fortify model's reliability.

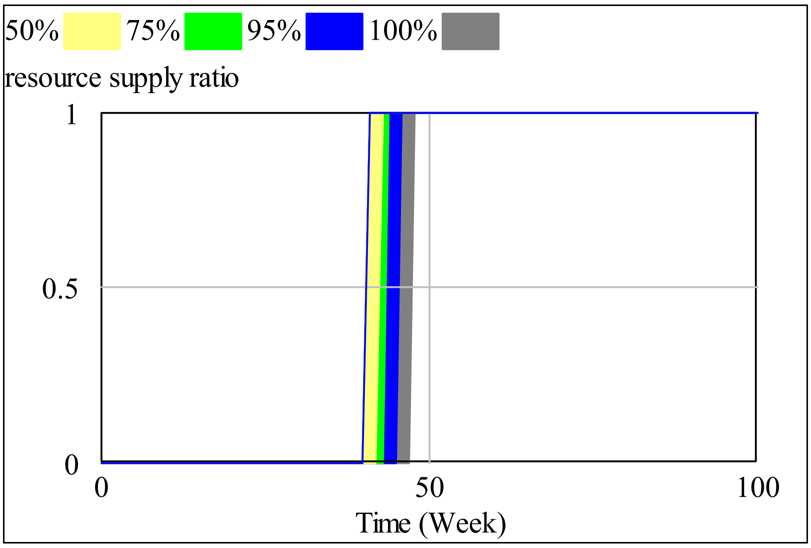


**Fig. 9** Probability of Resource Acquisition Time for Individual Facility Restoration

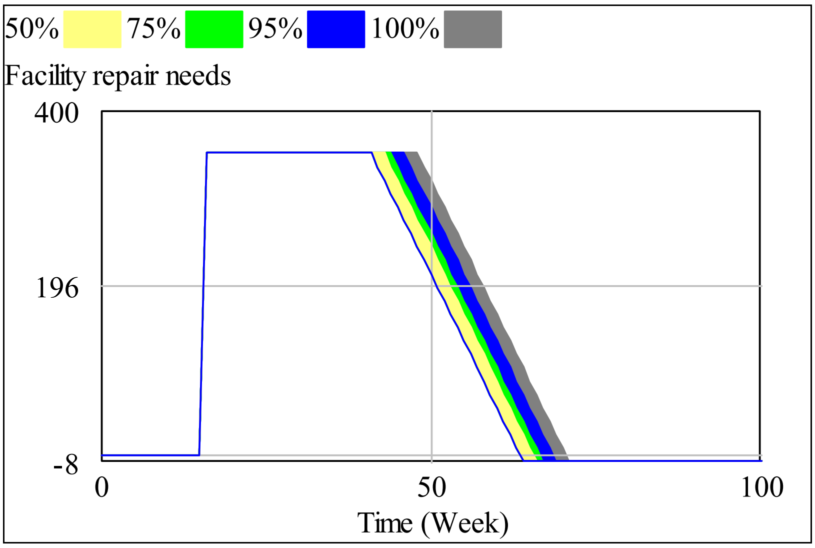


**Fig. 10** Expected Facility Restoration Progress

## Conclusions

To analyze regional-level recovery environment and its effects on an individual facility restoration project after a disaster event, this research attempted to develop a dynamic and integrated SD model that focuses on the effects of a recovery environment on resource supply and working conditions for restoration operations of facilities and infrastructures. These are affected by regional-level interdependent recovery process among different type of facilities within limited resources. The results of model simulation showed that a better understanding of the effects of post-disaster recovery environment (e.g., resource availability, required service availability, and their effects on restoration work efficiency) on individual facility restoration can support project managers to implement appropriate restoration planning to rapidly recover facility's functionality with reduced wastes of time, cost and resources. This model also has a potential to be further utilized for implementing more effective restoration plans for regional-level built environment with an understanding of regional recovery environment.

The model in this research is developed based on the existing research and theories on a disaster situation and a recovery process. Although it has an advantages in understanding complex and interdependent recovery process of regional built environment, it has limitations on reflecting detailed and physical specifications of impacts of disaster, damage generation, regional built environments, and recovery/restoration operations. To more accurately reflect reality and be able to be applied in actual recovery planning, the several future works are required with a hybrid modeling concept, as follows: (a) the more detailed and complex disaster and damage intensity functions need to be produced from existing disaster software that has the ability to estimate the potential losses in future events; (b) the more detailed information of regional built environment also needs to be analyzed from geographical and geological information system and/or facility information database; and (c) the process and operational details including resources for different types of restoration work need to be analyzed to enhance planning capability.

## Acknowledgements

This research was supported by a grant (12TRPI-C064106-01) from R&D Program funded by Ministry of Land, Infrastructure and Transport Affairs of Korean government.

## References

AbouRizk, S., Halpin, D., Mohamed, Y., and Hermann, U. (2011). "Research in Modeling and Simulation for Improving Construction Engineering Operations." Journal of Construction Engineering and Management, ASCE, 137(10), 843-852.

Chen, Y.-W., and Tzeng, G.-H. (1999). "A fuzzy multi-objective model for reconstructing the post-quake road-network by genetic algorithm." International Journal of Fuzzy System, 1(2), 85–95.

Chua, D. K. H., Yeoh, K. W., and Song, Y. (2010). “Quantification of Spatial Temporal Congestion in Four-Dimensional Computer-Aided Design.” Journal of Construction Engineering and Management, ASCE, 136(6), 641-649.

Dimakis, N., Filippoupolitis, A., and Gelenbe, E. (2010). “Distributed Building Evacuation Simulator for Smart Emergency Management.” The Computer Journal, 53(9), 1384-1400.

El-Anwar, O., El-Rayes, K., and Elnashai, A. (2009). “Optimizing largescale temporary housing arrangements after natural disasters.” Journal of Computing in Civil Engineering, 23(2), 110–118.

El-Rayes, K., and Moselhi, O. (2001). “Optimizing Resource Utilization for Repetitive Construction Projects.” Journal of Construction Engineering and Management, ASCE, 127(1), 18-27.

Harrison, J. R., Lin, Z., Carroll, G. R., and Carley, K. M. (2007). “Simulation Modeling in Organizational and Management Research” Academy of Management Review, 32(4), 1229-1245.

Hegazy, T. (1999). “Optimization of Resource Allocation and Leveling Using Genetic Algorithms.” Journal of Construction Engineering and Management, ASCE, 125(3), 167-175.

Holguín-Veras, J., Pérez, N., Ukkusuri, S., Wachtendorf, T., and Brown, B. (2007). “Emergency logistics issues affecting the response to Katrina: A synthesis and preliminary suggestions for improvement.” Transportation Research Record No. 2022, Transportation Research Board, Washington, DC, 76–82.

Holguin-Veras, J., and Jaller, M. (2012). “Immediate Resource Requirements after Hurricane Katrina.” Natural Hazard Review, ASCE, 13(2), 117-131.

Hu, W., Liu, H., and Yang, Q. (2004). “HLA-Based Emergency Response Plan Simulation and Practice over Internet.” Computer Science, 5553, 1203-1211.

Ibbs, W., and Nguyen, L. (2007). “Schedule Analysis under the Effect of Resource Allocation.” Journal of Construction Engineering and Management, ASCE, 133(2), 131-138.

Karlaftis, M. G., Kepaptsoglou, K. L., and Lambropoulos, S. (2007). “Fund allocation for transportation network recovery following natural disasters.” Journal of Urban Planning and Development, 133(1), 82–89.

Koto, T., and Takeuchi, I. (2003). “A Distributed Disaster Simulation System That Integrates Sub-simulators.” In First International Workshopon Synthetic Simulation and Robotics to Mitigate Earth-quake Disaster. accessed March 17, 2013. http://www.dis.uniroma1.it/res-cue/events/padova03/papers/index.html.

Kovel, J. P. (2000). “Modeling Disaster Response Planning.” Journal of Urban Planning and Development, ASCE, 126(1), 26-38.

Law, A., and Kelton, W. D. (2006). Simulation Modeling and Analysis, 3th, McGraw-Hill, pp. 1-11.

Le Masurier, J., Wilkinson, S., and Shestakova, Y. (2006). “An analysis of the alliancing procurement method for reconstruction following an earthquake.” Proc., 8th U.S. National Conf. on Earthquake Engineering, Earthquake Engineering Research Institute (EERI), Oakland.

National Disaster Management Institute of Korea (NDMI). “Research Reports.” accessed March 17, 2013.
http://www.ndmi.go.kr/ndmi_cms_iba/board/report/list.asp?show_no=85&check_no=2&c_relation=2&c_relation2=2.

Olshansky, R. B., Hopkins, L. D., and Johnson, L. A. (2012). “Disaster and Recovery: Processes Compressed in Time.” Natural Hazards Review, ASCE, 13(3), 173-178.

Orabi, W., El-Reyes, K., Senouci, A. B., and Al-Derham, H. (2009). “Optimizing Postdisaster Reconstruction Planning for Damaged Transportation Networks.” Journal of Construction Engineering and Management, ASCE, 135(10), 1039-1048.

Orabi, W., Senouci, A. B., El-Rayes, K., and Al-Derham, H. (2010). “Optimizing Resource Utilization during the Recovery of Civil Infrastructure Systems.” Journal of Management in Engineering, ASCE, 26(4), 237-246.

Pachakis, D., and Kiremidjian, A. S. (2004). “The Use of Simulation in Disaster Response Planning and Risk Management of Ports and Harbors.” Proceedings of 6th U.S. Conference and Workshop on Lifeline Earthquake Engineering, ASCE, Reston, VA, 425-434.

Pena-Mora, F., Han, S. Lee, S., and Park, M. (2008). “Strategic-Operational Construction Management: Hybrid System Dynamics and Discrete Event Approach.” Journal of Construction Engineering and Management, ASCE, 134(9), 701-710.

Pena-Mora, F., Thomas, J. K., Glparvar-Fard, M., and Aziz, Z. (2012). “Supporting Civil Engineers during Disaster Response and Recovery Using a Segway Mobile Workstation Chariot.” Journal of Computing in Civil Engineering, ASCE, 26(3), 448-455.

Pinelli, J., Simiu, E., Gurley, K., Subramanian, C., Zhang, L., Cope, A., Filliben, J. J., and Hamid, S. (2004). “Hurricane Damage Prediction Model for Residential Structures.” Journal of Structural Engineering, ASCE, 130(11), 1685-1691.

Pradhan, A., Laefer, D. F., and Rasdorf, W. J. (2007). “Infrastructure Management Information System Framework requirements for Disasters.” Journal of Computing in Civil Engineering, ASCE, 21(2), 90-101.

Riley, D. R., and Sanvido, V. E. (1995). “Patterns of Construction-Space Use in Multistory Buildings.” Journal of Construction Engineering and Management, ASCE, 121(4), 464-473.

Shen, L. Y., Tam, V. W. Y., and Drew, D. (2004). “Mapping Approach for Examining Waste Management on Construction Sites.” Journal of Construction Engineering and Management, ASCE, 130(4), 472-481.

Shoji, G., and Toyota, A. (2009). “Modeling of Restoration Process Associated with Critical Infrastructure and its Interdependency to a Seismic Disaster.” Proceedings of the 2009 Lifeline Earthquake Engineering in a Multihazard Environment, ASCE, Reston, VA, 647-658.

Song, J. X., and Li, J. (1995). “Simulation on accessibility of post-earthquake urban transportation system.” Journal of Natural Disasters, 5(1), 73-78.

Statistics Korea. “Korea Statistics Services.” accessed March 17, 2013. http://www.index.go.kr/egams/index.jsp.

Sterman, J. (2000). Business Dynamics: System Thinking and Modeling for a Complex World, Boston: Irwin Mcgraw-Hill, New York, NY.

Swan, R. C. (2000). “Debris Management Planning for the 21st Century.” Natural Hazard Review, 1(4), 222-225.

Williams, T. 2002. Modelling Complex Projects, Wiley, New York, 167–210.

Yotsukura, S., and Takahashi, T. (2009). “Framework of an Emergency Management System Using Different Rescue Simulators.” Advanced Robotics, 23(9), 1233-1246.

Zouein, P. P., and Tommelein, I. D. (2001). “Improvement algorithm for limited space scheduling.” Journal of Construction Engineering and Management, ASCE, 127(2), 116–124.