Assessment of Urban Disaster Resilience by Spatiotemporal Analysis of Demand and Supply

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ASSESSMENT OF URBAN DISASTER RESILIENCE BY SPATIOTEMPORAL ANALYSIS OF DEMAND AND SUPPLY

Eujeong CHOI[1], Max DIDIER[2], Junho SONG[3], Bozidar STOJADINOVIC[4]

ABSTRACT

The functioning of communities in contemporary urban settings relies heavily on the capacity of civil infrastructure systems (CISs) to supply services to satisfy the demand of the community. Natural disasters have, however, adverse effects on such systems. Moreover, damage to one CIS may spread to other CISs due to interdependencies. It is, therefore, essential to identify areas in an urban setting that are susceptible to service supply deficits. Resilient CISs are designed to avoid a service supply deficit, and/or to quickly recover their services in case of a shortage. In a holistic approach, the community demand and supply of a CIS are compared to each other to identify potential community sub-areas with a possible lack of resilience after a natural disaster. This study uses the Re-CoDeS (Resilience-Compositional Demand/Supply) framework for the purpose of identifying such areas through spatiotemporal analysis in the context of a seismic event. The post-disaster supply of a CIS is computed using the probabilistic seismic vulnerability of infrastructure components and system recovery models. The post-disaster demand is evaluated using the seismic performance of the building stock as a proxy for the vulnerability of the demand. Based on these results, the potential lack of resilience is computed for each community sub-area. The situation observed immediately after the disaster and the recovery path of the neighborhoods are displayed in a demand-supply plot to understand the spatiotemporal resilience pattern within the community. The presented framework is expected to help disaster managers to identify regions with low disaster resilience, and to elaborate emergency plans and retrofitting strategies in space and time to minimize a potential lack or resilience.

Keywords: Disaster Resilience; Civil Infrastructure System; Community; Demand; Supply; Recoverability

1. INTRODUCTION

Disaster resilience is an urban community's ability to minimize the socio-economic impact of a catastrophic event. The impact of a disaster could differ widely, depending on the preparedness of a community and on the post-disaster recovery. In fact, the speed and the pattern of recovering the original functions of a civil infrastructure system (CIS) and the community it serves after a disaster are as critical as the initial damage and losses. To improve urban disaster resilience, understanding the spatiotemporal evolution of the CIS and community resilience is an important step.

To date, various frameworks to assess the disaster resilience have been proposed in various research fields, including civil engineering, social sciences, and economics (Bruneau et al. 2003, Cutter et al. 2008, Francis et al. 2014). Major challenges of community-level resilience assessment remain, however, the complexity and the large size of communities, which make it difficult for researchers to understand the intertwined relationships between numerous community elements and their effect on community

[1] Doctoral student, Department of Civil and Environmental Engineering, Seoul National University, Seoul, Republic of Korea, ohyes@snu.ac.kr
[2] Doctoral student, Department. of Civil, Environmental and Geomatic Engineering, ETH Zurich, Zurich, Switzerland; didier@ibk.baug.ethz.ch
[3] Professor, Department of Civil and Environmental Engineering, Seoul National University, Seoul, Republic of Korea, junhosong@snu.ac.kr
[4] Professor, Department. of Civil, Environmental and Geomatic Engineering, ETH Zurich, Zurich, Switzerland; stojadinovic@ibk.baug.ethz.ch

functions.
To overcome some of these complexity-related challenges, we focus on the relationship between the community demand and the service supply of CISs. Since the availability of CIS services, such as electric power and potable water, have become indispensable for modern communities, lack of community resilience is defined hereafter as the gap between the community requirements for a service and the service-supplying capacities of CISs. Using a spatiotemporal resilience assessment framework, different geographical sub-areas of a city are examined in terms of the post-disaster evolution of service demand and supply over time, depending on the recoverability of CISs and community components. A concept of a "demand-supply plot" is proposed to understand the dynamic resilience patterns of the studied community in the spatial and in the temporal frame. The usefulness of identifying sub-area resilience patterns is shown in the case study of the community and the electric power supply system of several districts of Seoul (Republic of Korea) submitted to a scenario earthquake.
After Introduction, Section 2 surveys the existing research related to quantifying the community level disaster resilience. Section 3 describes the spatiotemporal resilience assessment framework proposed in this paper to map the evolution of urban community disaster resilience. After the case study presented in Section 4, the paper is concluded in Section 5.

2. LITERATURE REVIEW

In recent decades, engineering resilience assessments have been made at a wide range of levels – from the resilience of a single component to the resilience of a community. Depending on the level of detail of the assessment, different approaches are required. At both component and system levels, a 'resilience triangle' concept has been widely adopted to quantify resilience to natural disasters (Bruneau et al. 2003). It quantifies the post-disaster service performance over a certain period by measuring the area of the triangle formed by the graph of the system functionality plotted regarding the time, the so-called "resilience triangle". Unlike individual components of a systems, a community comprises numerous elements, including physical and social systems (system of systems). Additionally, reliable recovery models are not yet widely available. Therefore, adopting the resilience triangle framework directly at a community level is not trivial.
To assess post-disaster resilience of a CIS-Community system, a compositional demand/supply framework, Re-CoDeS (Resilience-Compositional Demand/Supply), has been proposed by Didier et al. (2017). While the resilience triangle concept mostly focused on the change of the physical capacity of structures and networks, the Re-CoDeS framework considers the resilience as a difference between the service demand of a community and the service supply of CISs. Through this approach, the societal context can be reflected in the resilience assessment. On the other hand, the community resilience clustering framework proposed by Choi et al. (2016) is based on both physical vulnerability and socioeconomic recoverability. Instead of modeling the highly complex and uncertain relationships between physical elements and other socioeconomic elements, sub-areas in the community are classified in terms of two resilience measures: their physical vulnerability and their socioeconomic recoverability. While the word 'vulnerability' is used as a metaphor which includes the socioeconomic vulnerability in some papers (Birkmann et al., 2013), physical and socioeconomic variables are separated in this paper. For example, only the physical variables including the seismic hazard and the inventory of structures are considered to obtain the seismic vulnerability of a community. In this context, to quantify the recoverability of a community, only socioeconomic variables have been reflected. The educational, social, economic, and political aspects are considered to measure the community recoverability. Eventually, these two resilience measures are being used to identify the resilience clusters in the community, and the spatially distributed resilience patterns within the community are illustrated in a GIS environment.
Each research topic summarized in this section broadened the community resilience assessment with novel approaches. Specifically, the Re-CoDeS framework adds a demand layer to the resilience triangle that links to community functions that reflect resilience in a societal context, and the resilience clustering framework considers both physical and socioeconomic indices in the quantitative resilience assessment. As shown in the following sections, we attempt to extend the community resilience assessment to a spatiotemporal frame.

3. THE SPATIOTEMPORAL RESILIENCE ASSESSMENT FRAMEWORK

To quantify the community demand and the infrastructure system supply for a spatiotemporal disaster resilience assessment, qualitative indices are selected for both. As conceptually illustrated in Figure 1, the post-disaster demand reduction of a sub-area is estimated from the physical vulnerability of the building stock, while the restoration of reduced demand is modeled though the building recovery model. On the other hand, post-disaster supply capacity of CIS is evaluated from the network topology and seismic vulnerability of the system components. Restoration of the supply capacity of system is evaluated from the recovery sequence and the CIS component recovery models. By comparing demand and supply conditions of each sub-area of the investigated community, the resilience pattern, as well as the lack of resilience of the community can be evaluated and illustrated in a spatiotemporal setting.

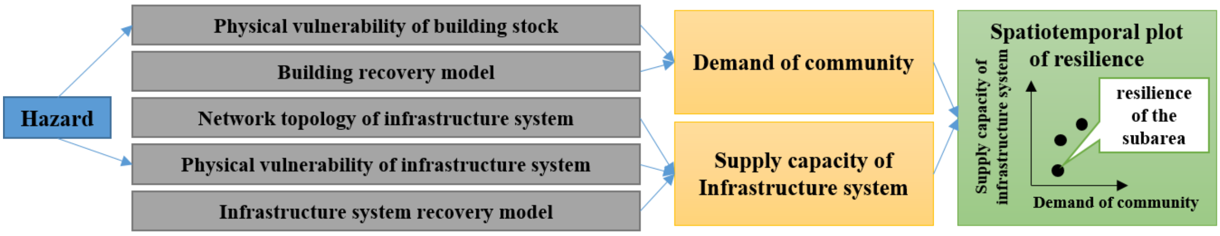

Figure 1. Proposed framework to assess the spatiotemporal resilience of a community demand – CIS supply system

3.1 Quantifying CIS service supply

A seismic risk analysis is performed to evaluate the post-disaster supply of the CIS immediately after the occurrence of the disaster. The post-disaster supply depends, among other factors, on the capacity of the network components, the network topology, the earthquake magnitude, the distance between the site of each component and the epicenter of the earthquake at interest, the soil conditions, the system service model, and, finally, the seismic fragility of the components of the CIS.
The evolution of the supply of the CIS is determined from the recovery sequence and the recovery model employed to determine the recovery of the system components. Even though the initial degradation of the supply relies on the disaster-resistance of the components of the system, the speed and the progress of the recovery depend on the preparedness and the resources of the system management group and operator. For the following case study, we use the recovery models provided in HAZUS (FEMA, 2003) as CIS component recovery models.

3.2 Quantifying community service demand

To evaluate the demand of a community for the service of a CIS, structural damage to the community built environment, such as building damage, is considered. In this study, we assume that the service demand of the community decreases in terms of the state of the building damage. After generating a scenario earthquake, the structural damage of every building in the area is examined using fragility curves that were developed for specific structural types, year of the construction, and the number of stories. The results of structural damage analysis are then used to assess the change of the demand for CIS service attributed to each structure after the scenario earthquake. Structures whose damage is classified as moderate or smaller are assumed to maintain the pre-disaster energy consumption. However, heavily damaged structures are expected to be evacuated and, thus, pose no demand for service anymore. The period from evacuation to re-occupation may be short or long, depending on the severity of damage after event and the recovery process. Thus, the resumption of demand is modeled in terms of the mean expected structural loss ratio after earthquake and the building restoration model. Finally, to obtain the total service demand of a neighborhood the demand of the different structures is aggregated for each of the sub-areas at each point in time when the demand is evaluated.

3.3 Spatiotemporal analysis of resilience patterns

To examine the resilience pattern of the different neighborhoods, the service demand and supply are plotted. Through the demand and supply plot achieved from the spatiotemporal resilience assessment framework, disaster resilience evolution of the neighborhood over the space and time could be understood.

For example, the classical loss and restoration of the service supply and the community demand after the disastrous event is illustrated in the Figure 2. The coordinates of each point in the plot represent the quantified community demand and the service supply available within a single neighborhood at a certain time. The location of this demand and supply point of a neighborhood shifts over time, regards on the recoverability of the community, CIS components,

and the CIS recovery sequence. The straight line across the demand and supply plot indicated the circumstance when the service supply and the community demand is equal, and it divide the lack of resilience zone and the service supply margin zone. The white colored zone is the service margin zone and the gray shaded zone is the lack of resilience zone. If the resilience point of the neighborhood located in the service margin zone in the demand and supply plot, as the day 30 in the Figure 2, the supply margin is the horizontal distance between the point and the zone dividing line. The resilience point at day 7 in the Figure 2, on the other hand, the distance between the resilience point and the zone dividing line indicates the lack of resilience of the neighborhood.

Additionally, recoverability of the infrastructure system and the community could be viewed from the gradient between the resilience points. For example, if the resilience point move toward the quadrant 2, it indicates the progress of the demand loss and the supply restoration. In the classical resilience progress illustrated in the figure, resilience evolution headed to quadrant 4 is not observed. For another example, when the amount of the restoration in demand and supply is equal, value of the neither lack of resilience nor service supply margin is influenced and the slope between the two-resilience points is parallel to the dividing line.

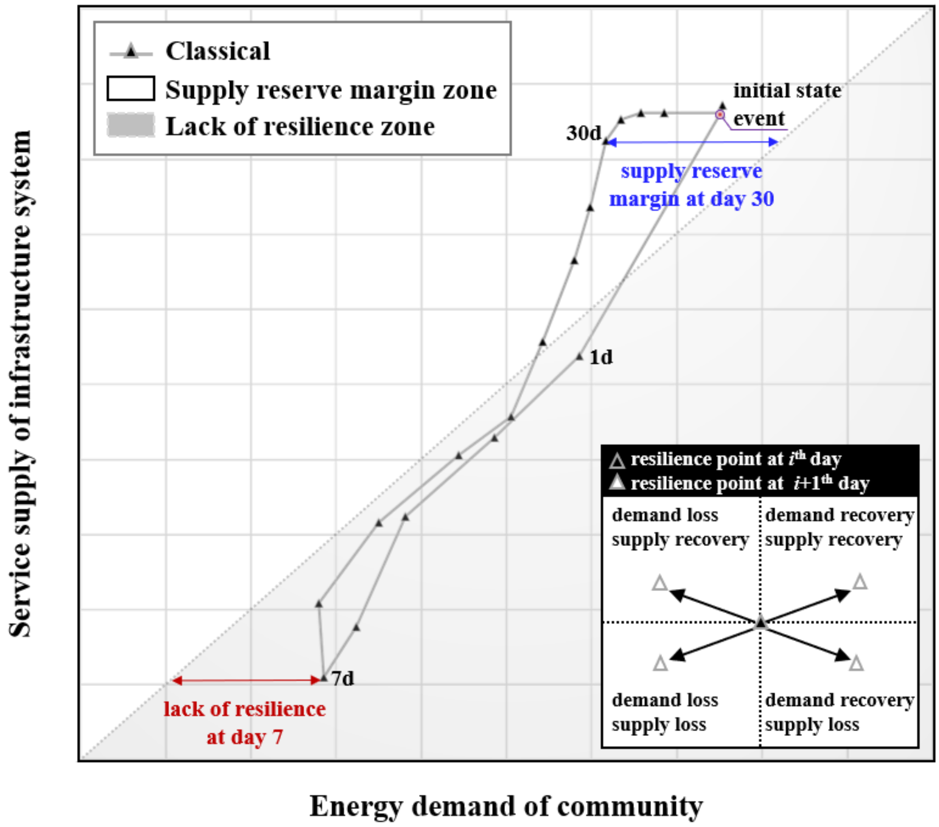

Figure 2. Demand and supply plot (examples to demonstrate concept)

4. CASE STUDY

To show the application of the proposed spatiotemporal framework, three neighborhoods located in southeastern Seoul submitted to a scenario earthquake are studied. A large part of the community and infrastructure system input data of the three districts of Seoul were collected from multiple open-sources (nsdi.go.kr, 2017).
As shown in the Figure 3, the rural area of Seongnam city, located 10 km from the southwestern boundary of Seoul, is selected as the location of the epicenter of the scenario earthquake in this case study. The selected location is close to historically observed earthquakes near Seoul. The scenario event was chosen to have a moment magnitude of 6.0 and the depth of 10 km. An earthquake with moment magnitude larger than the 6.0 is very rare because Korea peninsula is a low-to-moderate seismicity region. The selected earthquake scenario exceeds the historical record. Note that it was deliberately selected to demonstrate the spatiotemporal framework using a realistic community model under an extreme event. Therefore, even though the building and infrastructure inventories in this case study were built using real data, the results of case study are neither intended to present a probable post-disaster scenario nor to examine the actual seismic resilience capacity of the investigated community. In this paper, we focus on the demonstration of the diverse spatiotemporal resilience patterns in the demand and supply plot.
The seismic hazard and risk assessment software "Ergo" is used to generate an earthquake hazard scenario for Seoul (GFDRR, 2014). Using Ergo, an earthquake scenario is designed, and the corresponding structural damage of the building is analyzed sequentially. For the attenuation field, we select the CEUS Characteristic Event (Steelman et al., 2007), which use the combination of the multiple ground motion models, and the PGA values in the range of 0.11g to 0.89g were produced in the study area.

Figure 3. Location of the three neighborhoods and the epicenter

4.1 Supply of the power supply system

The case study considers the electric power supply system (EPSS) of the selected study area. While the exact coordinates of the power plants, substations, and transmission lines are not available, the relationships between the nodes and links of the electric power system are available publicly. For the purpose of this case study, the locations of the power transmission components were determined approximately. In addition to the approximate spatial coordinates, several additional assumptions were made to model the EPSS. The actual EPSS covers South Korea with high redundancy. Thus, a nationwide network analysis would need to be performed to examine the exact post-disaster condition of the part of the system included in the study area. Such analysis is, however, beyond the scope of this case study. Therefore, several modifications are made to the system. As illustrated in Figure 4(a), the network used in this paper consist of a selected subset of elements of the actual South-Korean EPSS.

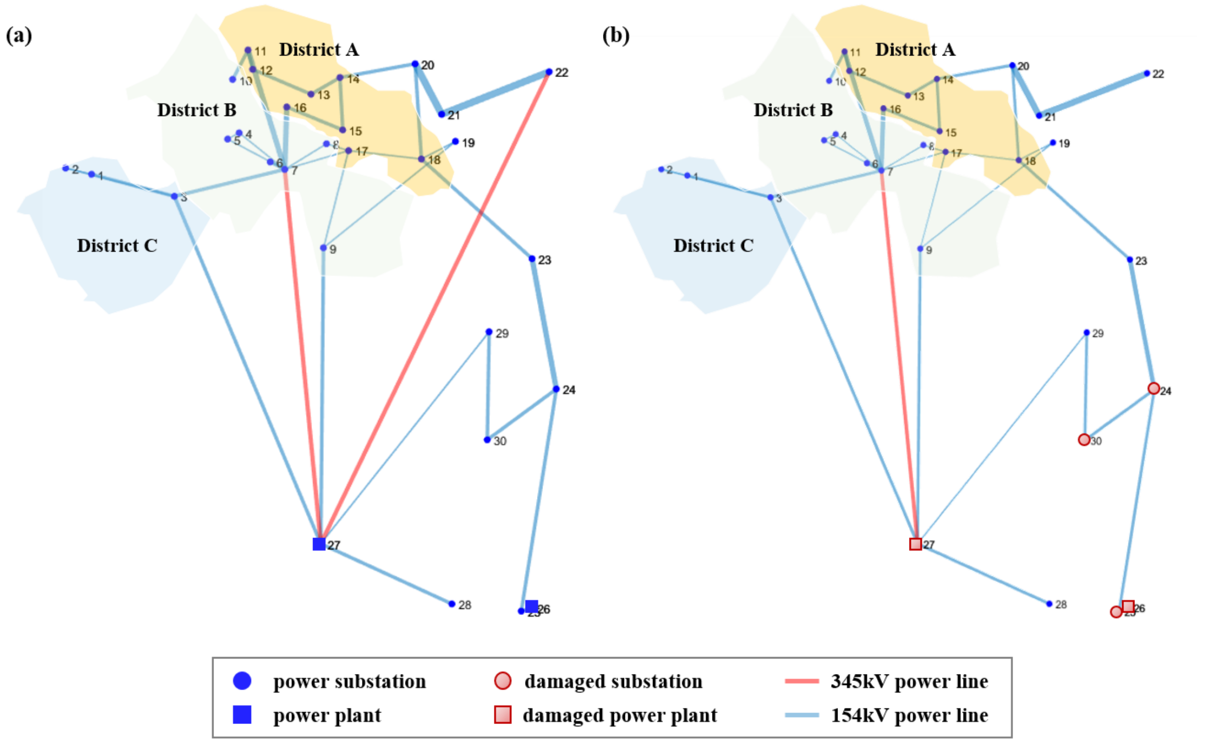

Figure 4. The EPSS network before (a) and after (b) the scenario earthquake

Table 1. Mean Building and EPSS component recovery time (Days)

Structure Type	Slight	Moderate	Extensive	Complete
Electric substation	1	3	7	30
Power plant	0.5	3.6	22	65
Multi Family Dwelling	5	30	120	240

Damage to the components of the EPSS is assessed using the earthquake ground motion intensity map generated in Ergo for the scenario earthquake, and the component fragility functions adopted from HAZUS (FEMA, 2003). The configuration of the damaged EPSS after scenario earthquake is shown in Figure 4(b). Several power substations got damaged (i.e. node 24, 25, 26 and 30).

EPSS component restoration models for damaged EPSS vary significantly depending on the type of the component and its post-disaster damage states. For instance, A completely damaged electric power system substation may require on average 30 days for full recovery, while an electric power generation facility is expected to need 65 days to recover. Add to the recovery model, recovery sequence also influences the evolution of the CIS service supply. In this paper, we selected recovery sequence manually, the repair started at node 27, followed by the 345kV power transmission edge, node 30, 24, 25, and 26. With this sequence, the evolution of the power supply of the EPSS is evaluated on a daily basis during the post-disaster recovery process.

4.2 Power demand of community

For this case study, the building inventory of the investigated neighborhoods are obtained from the 'Korea National Spatial Data Infrastructure Portal.' This national spatial data service provides diverse spatial information, including data on the parcels, buildings, roads, rivers, and other elements of the urban environment (nsdi.go.kr, 2017). In particular, the coordinates of the buildings are of particular interest in this case study. The location data is matched to the earthquake ground motion intensity map produced by Ergo in order to determine the intensity of the ground motion excitation at the location of individual buildings. Then, the structure type, building area, height, and a number of stories are used to find the seismic fragility curve that match each building best (Steelman et al., 2007). For the structure type, 11 types including concrete frame with concrete shear wall, the steel frame, and unreinforced masonry were considered. In terms of the occupancy type, residential, commercial, industrial, religion, government, and education were considered.

Fragility mapping is performed using the opensource software Ergo since the neighborhoods includes a large building inventory of more than fifteen thousand buildings. With the large amount of data set, building structural damage analysis using the fragility mapping is efficient. As the output, the probabilities of having each damage state, i.e. insignificant, moderate, heavy, and complete, was calculated for each building. From the calculated results, an overall expected loss ratio was also evaluated. The results of the building damage analysis within the community is shown in Figure 5. The district on the right-hand side which is close to the epicenter is estimated to have higher mean expected structural loss ratio compared to the other areas.

Figure 5. Post-earthquake mean expected structural loss ratios of the building stock in the investigated community immediately after the disaster (before any recovery)

To estimate the electric power demand reduction at the community level, the damage building inventory was further analyzed to determine the remaining demand posed by each structure, at the beginning and throughout the recovery process. The pre-disaster demand of each building was estimated using the annual electric power consumption report (Kepco.co.kr, 2017). The report addressed the electric consumption at a neighborhood-level, so the power demand of each building is assumed using the ratio of building area over total building area in the district. From the pre-disaster power consumption and the post-disaster mean expected structural loss ratio illustrated in Figure 5, the post-disaster demand of each building immediately after the disaster was evaluated. The recovery trend of the community demand after disaster is estimated using the HAZUS building recovery table. As the building inventory recovers, the demand for the power also increase and eventually recovered to the original power consumption. Finally, the power demand within the community is estimated from the aggregation of the power demand of each building.

4.3 Results

Based on the analysis of the electric power demand of the investigated community and the power supply of the EPSS evaluated in this case study, the power demand and supply plot are created and shown in Figure 6. The plot shows mean day-long aggregate demand and supply. In the demand and supply plot, 5 resilience state were computed (Pre-disaster, right after the disaster, when the supply capacity was restored in day 3, 30, and 120) for each district.

In terms of the pre-earthquake power demand and supply condition of the three-investigated neighborhood, districts A and B have a high reserve ratio, while district C has a low reserve ratio, with an electric power supply only 2% larger than the electric power demand. After the scenario earthquake,

however, all three districts experienced lack of resilience due to damage to the electric power generation facilities. The shaded area is the lack of resilience zone where demand is higher than the supply, people dwelling in three community can experience the lack of power supply after the earthquake.
As indicated in the demand and supply plot, district A is most prone to lack of resilience right after disaster despite the relatively large power reserve ratio and the loss of demand. Since the initial service demand within the district A was relatively high, post-disaster community demand is larger than others even it is closest to the epicenter of the scenario earthquake, and suffered the most building damage.
Under the assumption that power supply manage group is prepared with the emergency recover resource and expertise, service supply fully recovered in 3 days in district C and 30 days in A and B. Compared to the community demand restoration speed, it is a relatively fast process. Therefore, in the selected seismic disaster scenario, three communities experience severe but relatively short lack of resilience regarding power supplies.

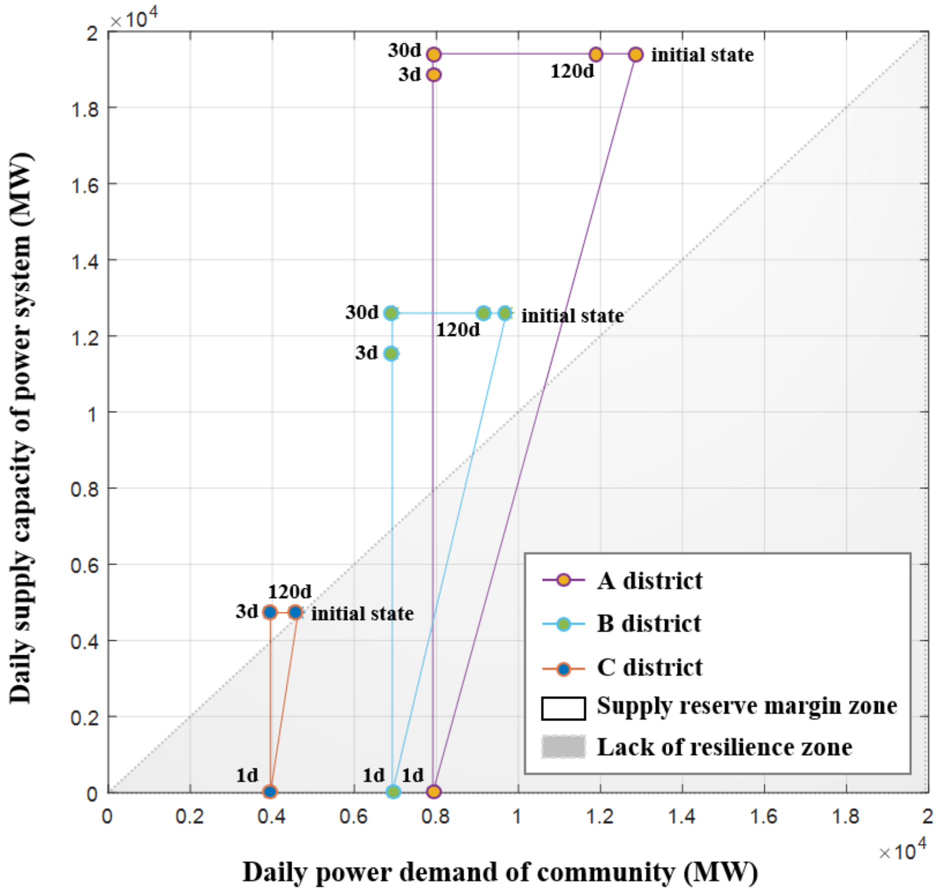

Figure 6. Daily power demand and supply plot

5. CONCLUSION

To examine the different resilience of the neighborhoods in a city, spatiotemporal resilience assessment framework was proposed with consideration of the post-disaster evolution of supply capacity of CISs and the demand of community. In addition, the “demand-supply” evolution plot was presented to illustrate the dynamic of the resilience pattern in the spatiotemporal frame. Identification of lack of resilience in the demand-supply plot using proposed framework is expected to enhance resilience-informed decision making in urban disaster planning. By identifying the neighborhoods with the low disaster resilience in terms of time and space, emergency restoration and pre-disaster resilience planning in spatiotemporal frame which minimize the potential lack of resilience could be elaborated.

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