A study on self-sufficient buildings against disaster: Survey of hospital facilities in Japan

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SUMMARY:
During lifeline disruptions after an earthquake, certain facilities are required so that the functioning of hospitals is not disrupted. High-performance building equipment has recently been installed in hospitals from the viewpoint of environmental, financial, and disaster management. For this study, we conducted a survey that targeted hospitals in order to understand the condition of the energy and water supply facilities as well as the disaster preparedness of each hospital. We also investigated the problems associated with the measures taken to prevent the interruption of commercial power supply at 90 hospitals, taking into account the rolling blackouts after the Great East Japan Earthquake. We present the concept of self-sustaining zones that surround hospitals and will improve the local functionality when lifelines are disrupted.

Keywords: lifeline disruption, facility management, hospital

1. GENERAL INSTRUCTIONS

During lifeline disruptions after an earthquake, facilities that act as disaster management solutions are required for maintaining the functions of a hospital building. Disaster base hospitals, which have been designated and established in Japan since the Kobe earthquake in 1995, are meant to provide medical care during and after major disasters. Moreover, from an environmental and financial view point, facilities that act as energy-saving solutions are required. Recently, various types of high-performance building equipment have been installed in regional general hospitals.

Accordingly, we conducted a survey targeting disaster base hospitals, one of the most important buildings for emergency management in the Tokyo capital region, to better understand both the condition of the energy and water supply facilities and the disaster preparedness of each hospital. We also investigated the problems associated with measures taken to prevent the interruption of commercial power supply at 90 disaster base hospitals, taking into account the rolling blackouts in the aftermath of the 2011 Great East Japan Earthquake.

Further, we showed the suitability of a hospital building to act as a core of a distributed self-sustaining district on the basis of the results of the survey and the location of each hospital. Such self-sufficing and independent buildings will improve the local ability to handle lifeline disruptions and community continuity during these disruptions.

2. SUMMARY OF THE QUESTIONNAIRE SURVEY

We conducted a questionnaire survey and interviews targeting 134 disaster base hospitals in the capital region (Tokyo, Kanagawa, Chiba, and Saitama Prefectures) of Japan; the survey was conducted from 2010 to 2011. The questionnaire contained items related to building structures, energy and water supply facilities, disaster management preparedness, and energy and water consumption per month.

The number of hospitals that answered the questionnaire was 78; the response rate was 58%. **Table 2.1** summarizes an outline of the survey.

Table 2.1. Summary of questionnaire survey

	TOKYO	KANAGAWA	CHIBA	SAITAMA
Period	October. 2010 – May. 2011			
Number of Disaster Base Hospitals	70	33	19	12
Number of Recoveries	39	21	10	8
Response Rate	55.7%	63.6%	52.6%	66.7%

3. OPINIONS ON CONTINUITY OF BUILDING FUNCTIONS

The opinions of hospital facility managers on the continuity of the functioning of their own institutions in the event of an earthquake are as follows. Fig.1 shows opinions that are related to managing the continuity of functions and resiliency building during major earthquake disasters. More than 40% of the hospitals said that it is either impossible or very difficult to ensure building functions are not disrupted as part of disaster management (**Fig.1**). **Fig.2** shows the weaknesses in the functioning of the building during a major earthquake disaster (Multiple Choice Question). The primary factor that makes hospital facility managers uneasy is the disruption of the water or electric power supply. Approximately 30% of them are uneasy about the earthquake resistance capacity of the hospital buildings although this figure is lower than that of the disruption of lifelines.

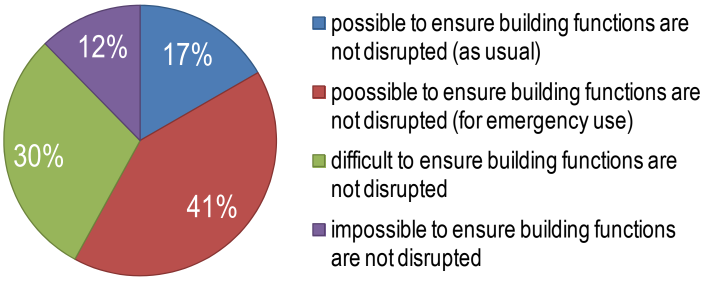

Figure 1. Opinions on the continuity of building functions during disasters (N=69)

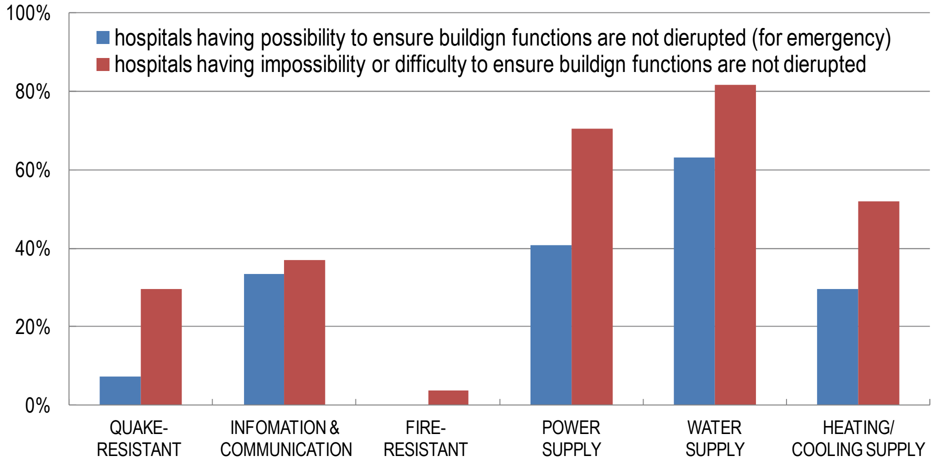

Figure 2. Weaknesses in the functioning of the building during a major earthquake disaster

We hypothesized that the disruption in supply-type lifelines had a great impact on hospitals in the event of emergencies; we conducted a multivariate analysis of the reasons hospital facility managers found it difficult to maintain hospital functions during a disaster. **Table 3.1** summarizes the results of the multivariate analysis—quantification theory 2—that was conducted to clarify the influence of each function on the management of entire building during a disaster. Using dummy variables for categorical variables, we conducted a qualitative discriminant analysis, which was termed the quantification theory 2 by Hayashi (1950, 1952, 1954). A comparison between the sense of security that a manager felt by managing the entire building and the sense of security that a manager felt by managing each building function was made by using Hayashi's quantification method. 54 samples were used. The explanatory variables included six items based on the questionnaire survey. Each value influenced the contribution ratio of the sense of security that the managers felt by managing the entire building. A higher value implied that a manager felt a strong sense of security when managing a hospital building as a disaster base, while a lower value implied that the manager felt a poor sense of security for the same. "Quake resistant" was the strongest reason that influenced the managers' sense of security. Managers who felt uneasy about the quake resistance of the hospital building structure were more inclined to believe that the building had a higher chance of succumbing under an earthquake. As a result, the accuracy of this estimation was approximately 75%, although the correlation ratio was not sufficient (0.23).

Table 3.1. Results of the quantification theory 2 for the influence of each function on building management

ITEM	CATEGORY	SAMPLES	CATEGORY SCORE	RANGE
Quake Resistant	SAFE	44	0.32	1.75
	UNEASE	10	-1.42	
Information & Communication	SAFE	35	-0.09	0.26
	UNEASE	19	0.17	
Fire Resistant	SAFE	53	0.02	1.30
	UNEASE	1	-1.27	
Power Supply	SAFE	24	0.37	0.67
	UNEASE	30	-0.30	
Water Supply	SAFE	15	0.55	0.76
	UNEASE	39	-0.21	
Heating / Cooling Supply	SAFE	32	0.35	0.86
	UNEASE	22	-0.51	

4. WATER SUPPLY

4.1. Water Supply System

Details of water supply equipment are described briefly as follows. Elevated water tank systems are selected in more than 90% of the hospitals. These hospitals can use the water in the tank during the suspension of water and power supplies when an earthquake occurs. On the other hand, some hospitals use a direct connecting system or a pressure tank system. These hospitals will not be able to obtain water without electric power supply. Moreover, approximately 20% of the hospitals have water in the ice or water storage tanks for air conditioning. A reclaimed water system is adopted by 30% of the hospitals, well water is used by 30% of the hospitals and rain water is used by 17% of the hospitals because a water recycling system has recently been installed in these hospitals on the basis of environmental considerations.

4.2. Water Supply Equipment

Fig.3 shows the relationship between the capacity of water tanks per unit total floor area and the construction or reconstruction year of each hospital. A reception tank system provides the capability of using storage water in the tank during a water supply or power supply disruption. However, the recently, capacity of the water tank has been decreased. Moreover, some hospitals have started using a direct connecting system that has small water tanks; however, it is not possible to supply water using this system when the public water supply is interrupted. The average capacity of water tanks (receiving tanks and the elevated tanks) used in hospitals is 8.5 L/m^2. If each tank is completely filled with water, hospitals have water supply for one day to meet the demand (2.77 m^3/m^{2}year) on the basis of a survey conducted by Takaguchi (2009). If the water tanks for non-potable water are included, the average water tank capacity is 14.3 L/m^2 (which is approximately the demand for two days).

Further, the period for which they can use water during water supply disruptions is approximately 27 h, as revealed by the responses to the questionnaire. It is considered that these buildings must plan the use of storage water in the tanks during water supply disruptions because the storage water is not sufficient to meet the complete water demand in hospitals.

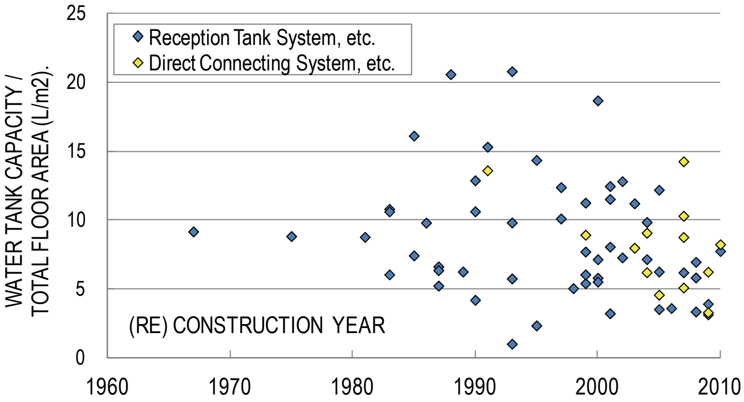

Figure 3. Relationship between water tank capacity per unit total floor area and construction or reconstruction year

4.3. Sense of Security about Water Supply

Table 4.1 summarizes the results of the multivariate analysis—Hayashi's quantification theory 2—which was conducted to clarify the influence of the characteristics of the water supply equipment on the sense of security in the case of water supply disruptions. 54 samples were used. The explanatory variables included four items concerning the water supply system and the equipment profile based on the survey. "Water tank capacity" is the total capacity of tanks for potable and non-potable water and is categorized by the period of meeting the demand (2.77 m^3/m^{2}year). "Year built" is the construction or reconstruction year of each hospital building. "Water demand" is the water consumption per total floor area in 2009 and is categorized by the standard consumption. "Water supply system" specifies whether a direct connecting system is included. Each value influences the contribution ratio of the sense of security during a water supply disruption. A higher value implies a strong sense of security with respect to the water supply, whereas a lower value implies a poor sense of security for the same. "Water tank capacity" is the strongest of all the reasons that the hospital facility manager would have with respect to the sense of security about the building water management. It is considered that the sense of security is propagated by water supply systems that have large water tanks, that have been constructed recently, and that economize water consumption; these systems do not included a direct connecting system. Consequently, the potential of the sense of security during a water outage was found to be approximately 63% accurate, although the correlation ratio was not sufficient (0.11).

Some hospitals answered that "we can carry out building facility functions during water supply disruption with well water." The number of hospitals that use well water, rain water, and reclaimed water systems has increased recently (The adoption rate for each of these three systems is 30%, 17%, and 30%). These are useful systems for improving the supply reliability in the case of an emergency. It is important to prepare for the disruption of water supply, with storage water of not only the top water tank but also an extra water tank, rain-water tank, hot-water storage tank, heat storage tank, or fire-prevention water tank in each building. It is also important to consider the waste-water treatment system or the emergency water supply plan of the local government.

Table 4.1. Results of quantification theory 2 for the relationship between the sense of security during a water outage and the characteristics of the water supply equipment

ITEM	CATEGORY	SAMPLES	CATEGORY SCORE	RANGE
Water Tank Capacity (period to meet demand)	3 days or over	8	1.35	1.70
	2 - 3days	11	0.11	
	within 2 days	35	-0.34	
Year Built or rebuilt	after 2005	11	1.31	1.65
	before 2004	43	-0.34	
Water Demand per total floor area (m^3/m^2 year)	under 2.77 (Low)	22	0.55	0.93
	2.77 or over (High)	32	-0.38	
Water Supply System	Reception Tank, etc.	42	0.14	0.63
	Direct Connecting, etc.	12	-0.49	

5. ENERGY SUPPLY

5.1. Energy Supply System

Details of power and gas supply system are described briefly as follows.

A spot network power receiving system has been installed in 13% of the hospitals, a loop receiving system in 8% of the hospitals, and a double-line power supply system in 57% of the hospitals. Approximately 75% of the hospitals have adopted the systems as preparation for power supply disruption. On the other hand, some disaster base hospitals receive electrical energy from only one line. All hospitals have power generation facilities; one-third of them depend on the facilities for their regular power supply, and the other two-thirds only use the facilities during emergencies.

There are two common types of gases (city gas and liquefied petroleum gas) used in Japan and city gas is the main type used in the capital region. Approximately 7 percent of the disaster base hospitals responded that do not use city gas. Approximately 45 percent of the hospitals stated that they use high-pressure city gas or medium-pressure city gas transmitted through pipelines that have high earthquake resistance. The other 48% of the hospitals said that they use low-pressure city gas. Disaster base hospitals do not necessarily adopt a high-earthquake-resistance lifeline system.

5.2. Energy Supply Equipment

Fig.4 shows the relationship between the ratio of the self-generation capacity to the contracted power demand and the total floor area in each hospital. The average ratio of the self-generation capacity to the contracted power demand is 67%, and the average self-generation capacity is 1,800 kW in the hospitals. On the other hand, Inagaki (2012) showed that the average ratio was 60% and that the average capacity was 900 kW in the local government offices. It is considered that the generators in hospitals are larger than those in other type of buildings. In particular, hospitals that use a generator daily tend to have a large generator. In such hospitals, the average ratio of the self-generation capacity to the contracted power demand is 78%, and the average self-generation capacity is 2,300 kW. In this study, the contracted power demand takes into account the self-generation capacity if the building has daily-use generators. Some relatively small hospitals need to take measures against power disruption because the ratios of the hospitals vary widely.

In hospitals that have a large power generation capacity, the facilities have improved and co-generation systems have been installed recently. These systems help improve the reliability of the power supply and the heat supply in the absence of a commercial power supply. Moreover, some buildings have generators with sufficient capacity; however, they do not necessarily have sufficient fuel storage. Fuel storage and procurement are important to maintain a building’s electricity facility.

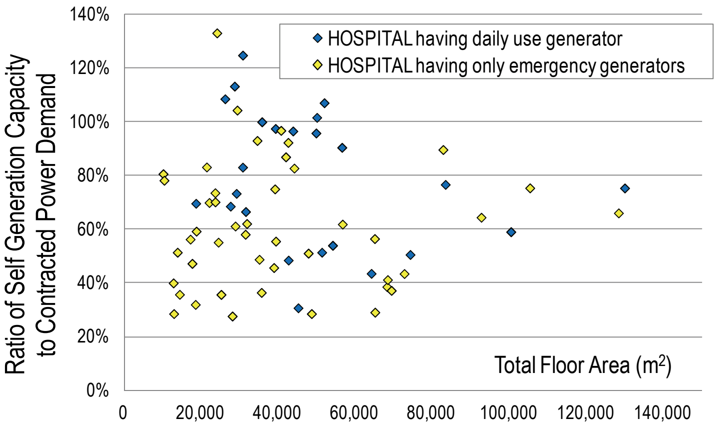

Figure 4. Relationship between ratio of self-generation capacity to contracted power demand and total floor area

5.3. Sense of Security about Power Supply

Table 5.1 summarizes the results of the multivariate analysis—Hayashi's quantification theory 2—which was conducted to clarify the influence of the characteristics of power receiving system and generators on the sense of security in the case of commercial power supply disruptions. 55 samples were used. The explanatory variables included five items concerning each power equipment's profile based on the survey mentioned earlier. Each value influenced the contribution ratio of the sense of security during a power outage. A higher value implied a strong sense of security for maintaining an electrical power function by self-generation, whereas a lower value implied a poor sense for the same. "Continuous operation periods of generator" was the strongest of all the reasons for the hospital facility manager to have a sense of security about the building's power management. "Power receiving system" was also a strong reason. It was considered that the sense of security would be provided by a spot network or loop power receiving system and a generator that could be operated continuously for a long period, that had sufficient capacity to meet the contracted power demand, and that was installed recently and operated daily. Consequently, the potential of the sense of security during a power outage was found to be approximately 76% accurate, although the correlation ratio was not sufficient (0.23).

Table 5.1. Results of quantification theory 2 for the relationship between the sense of security during a power outage and the characteristics of power supply equipment

ITEM	CATEGORY	SAMPLES	CATEGORY SCORE	RANGE
Power Receiving System	Spot Network	8	0.74	1.12
	Loop	6	0.59	
	Double Line	29	-0.17	
	One Line	12	-0.39	
Continuous Operation Periods of Self-Generator (MAX)	72 hours or over	26	0.39	1.44
	24 - 72hours	18	0.07	
	within 24 hours	11	-1.05	
Ratio of Self-Generation Capacity to Contracted Power Demand	60% or over	30	0.31	0.68
	under 60%	25	-0.37	
Installation Year of the Newest Self-Generator	after 2005	19	0.43	0.66
	before 2004	36	-0.23	
Operation of Self-Generator	Daily	21	0.08	0.12
	Emergency only	34	-0.05	

6. ROLLING BLACKOUT

Rolling blackouts were implemented in the Tokyo capital region (except the central part of Tokyo) from March 14 to 28 because of an electric power supply shortage after the Great East Japan Earthquake (March 11, 2011). We also investigated the problems associated with the measures taken to prevent the interruption of commercial power supply at disaster base hospitals in the capital area.

The interview surveys involving 90 hospitals were conducted in May 2011.

Fig.5 and **Fig.6** show the situation of a rolling blackout in disaster base hospitals in the Tokyo capital area. 40 hospitals had a commercial power outage one to seven times on weekdays. The duration of each blackout was approximately three hours. 10 percent of these hospitals switched lines and received commercial power supply from two transformer substations. 90 percent of the hospitals generated power themselves. Hence, the blackouts do not pose serious problems directly affecting patients' lives in each hospital. Some hospitals opened their doors to the public during power outages. The following are the main problems during commercial power supply interruptions. Incidentally, the hospital buildings were not damaged deeply excepting two hospitals that damaged by tsunami and liquefaction in Chiba Prefecture.

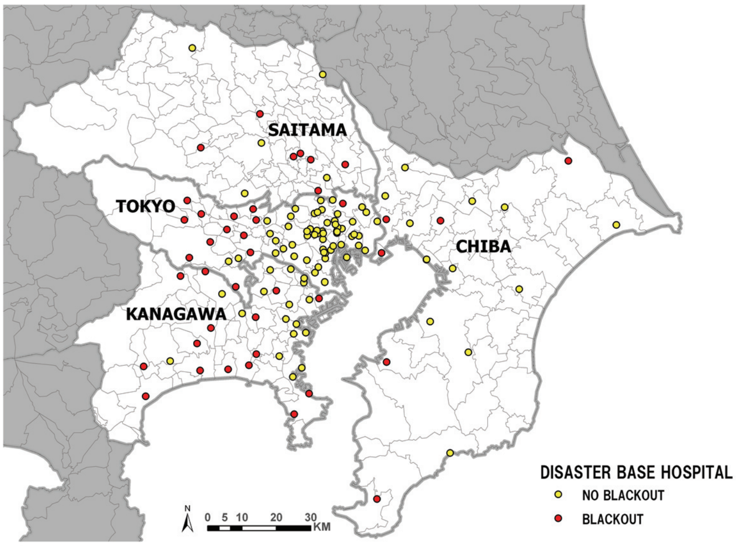

Figure 5. Rolling blackout in disaster base hospitals in Tokyo capital area

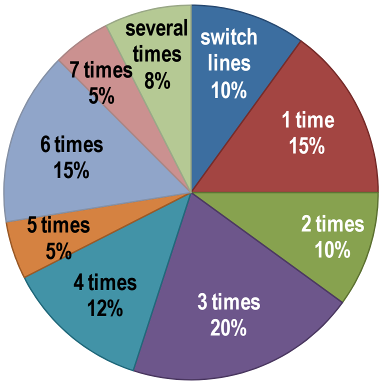

Figure 6. Times of blackout (N=40)

6.1. Generator

Many hospitals started a self-generator in the manual mode before the blackout starting time to avoid problems related to medical devices because they did not know the exact time when a blackout would start. They need to reselect important electrical machines connected to the emergency power outlet and install more generators, storage batteries, or UPSs.

6.2. Medical Devices

Many hospitals could not continue their business because medical devices were turned off before and after a rolling blackout to prevent problems caused by a short interruption and to reduce the power demand. In case such problems occurred, a considerable time was spent on repairing the medical devices because it was difficult to send for the staff of the manufacturer or obtain parts of the devices.

6.3. Fuel Procurement

Many hospitals could not procure fuel for generators and felt insecure about the fuel shortage. Business continuity depended on not only the capacity of the generator but also the fuel stock. Government or municipal hospitals could procure fuel with comparative ease because there were agreements between the government and an energy company. Priority needs to be given to an emergency facility. The city-gas generators work without such a problem.

7. CONCEPT OF DISTRIBUTED SELF-SUSTAINING ZONE

It is considered that hospitals having high-performance energy facilities have the potential to be a core of an area energy network from the environmental point of view because they have large energy demand, and some of them have large-capacity generators and have installed a co-generation system for regular use. It is important to construct self-sufficient buildings or districts for effectively dealing with lifeline disruptions caused by an earthquake. **Table 7.1** presents some tools for planning a self-sufficient building and district. In this section, we select hospitals as a candidate for a core building of not only an area energy network but also a self-supporting zone and present the concept of a distributed self-sustaining zone.

Table 7.1. Tools for planning self-sufficient building and district

	WATER	ELECTRIC POWER	HEATING
STORE	Water tank	Battery	Heat storage tank Hot-water storage tank
CREATE	by Reclaimed water system	by Generator	by Co-generation system
UTILIZE ENVIRONMENT	Well, Rain, River or Sea water	Solar, Wind, Hydroelectric, Geothermal or Wave Power	Solar thermal energy
DIVERT	Heat storage tank Hot-water storage tank Fire-prevention water tank		
EMERGENCY RELIEF	Water supply truck or ship	Vehicle-mounted generator	Trans heat container
SHARE	Emergency water supply tank & hydrant	Energy Interchange system between buildings	
		Smart grid	District heating & cooling

We estimated the heat demand and the heat load density using the result of a building survey and created a heat load density map to search the site of the candidate for an area energy network. In this case study, the commercial and residential sector energy is targeted. **Fig.7** presents the heat load density and the hospital sites in Kanagawa. It was clear that disaster base hospitals were in the higher-density mesh of each area. A high density area corresponding to more than 4.2 TJ/ha per year has the potential to be adapted for an area energy network site and sharing high-performance facilities (Committee for Promoting District-scale Energy Use, 2005). It is considered that approximately 70% of the hospitals have the potential to be adapted for an area energy network site. There are more hospitals having the potential in Tokyo. Moreover, hospitals have high-performance facilities to continue business during a disaster, referring to the survey results. The high-performance and large-capacity facilities are not always operated at full capacity. There are capabilities of supplying energy to neighbouring buildings in the off-peak time and between seasons. In addition, the total energy consumption will also be reduced if operating high-performance machines take priority in each area. As mentioned above, it is considered that a disaster base hospital has the potential to be a core building of a self-sustaining zone to improve not only energy saving but also energy security.

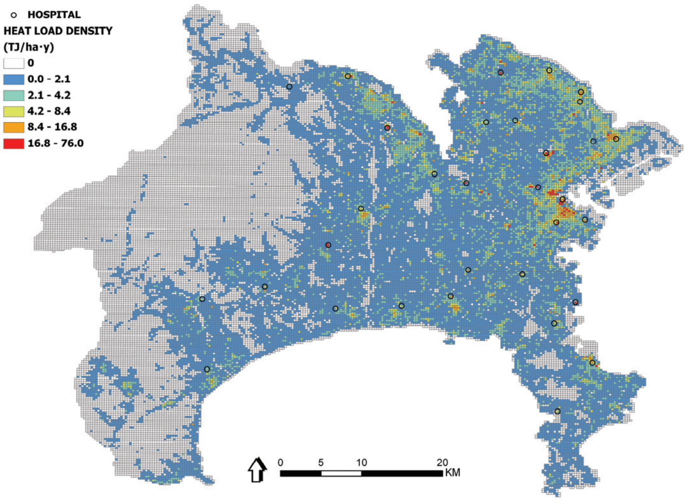

Figure 7. Heat load density and disaster base hospital sites

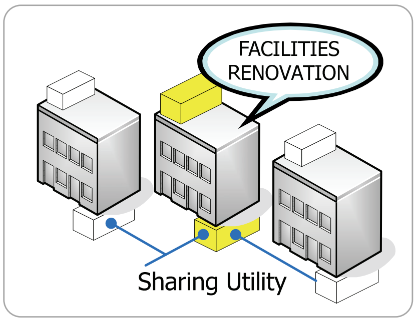

Figure 8. Image of sharing and renovating facilities

Fig.8 presents an image of sharing high-performance facilities and renovating degraded facilities in the district (Inagaki, 2008). If some buildings coordinate their sharing and renovating facilities and manage other resources, it will be possible to construct and maintain a distributed self-sustaining zone using building stock for earthquake disaster reduction in an urban area.

8. CONCLUSION

Based on a survey targeting hospitals in Tokyo capital area of Japan, it was clear that disaster base hospitals tend to have high-performance energy facilities for supporting business continuity during a disaster. On the other hand, it was also clear that using only the storage water during public water supply disruptions is insufficient. The quantitative influence of each facility on the sense of security that hospital facility managers felt was also statistically measured, the results of which have the potential to significantly improve the equipment's efficiency. In the case of commercial power supply interruption, it was found that not only facilities but also fuel stock or facility operations were important to ensure the buildings' functions. Moreover, some tools for planning a self-sufficient building and district and the concept of a distributed self-sustaining zone to improve local functionality under lifeline disruptions were presented.

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