CLASSIFICATION OF URBAN AREAS BY CHARACTERISTICS OF POWER LOAD CURVES

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Abstract: Modern societies heavily rely on electric power. These societies suffer functional damage due to power outage when natural disasters such as earthquakes and typhoons strike. As the first step for developing a new methodology for estimating the effects of power outage on city functions considering the characteristics of the area, and time and duration of outage, a database is made which consists of regional characteristics and electric power demand in the Tokyo Metropolis using geographic information system (GIS). Power demand is examined as a function of time, season and region. Through the analysis, it is found that there are several typical curves and that classification of the areas by such typical load curves might be possible. With a statistical technique, four elemental load curves of residential, office, industrial and entertainment components are calculated. Assuming that every load curve is a combination of the four elemental curves, the contribution rate of the four elements in each area is calculated. Using the contribution rate, the areas could be classified considering the characteristics of their load curves. The results show that this classification can be applied to the estimation of the effects of power outage on various city functions considering the time and duration of outage, and the characteristics of the area.

1. Introduction

Although people may not realize it, modern societies in developed countries heavily rely on electric power. In consequence, these societies suffer functional damage due to power outage when natural disasters such as earthquakes and typhoons strike. For example, severe damage due to power outage was reported during recent earthquakes such as the Loma Prieta Earthquake (17 Oct. 1989, M7.1)[1], Kushiro-Oki Earthquake (15 Jan. 1992, M7.8)[2], and Northridge Earthquake (17 Jan. 1993, M6.7)[3]. Typhoon 9119, the 19th typhoon in Japan in 1991, significantly affected critical lifelines, particularly, the electric power supply, throughout most of southwestern Japan. At the peak of the outage, approximately 7.1 million customers (about 13 % of all customers in Japan) were without power. In Hiroshima City, the 10th largest city in Japan with a population of 1,080,000, about 390,000 households, or 99 % of the total, were without power and the power outage affected various city functions[4].

Although the safety levels of the electric power facilities against natural disasters are getting higher with the improvement of material, design and construction technologies, the study from the functional point of view is not enough and a new type of damage brought about by malfunction is of concern. Since natural disasters which do not cause severe structural damage but lead to various damage due to malfunction have happened, we acquired a new understanding of the effects of power outage in urban areas.

The effects of power outage include no lighting, interruption of water supply and sewage work, traffic, on-line bank service, broadcast and telecommunications, etc. We try to study

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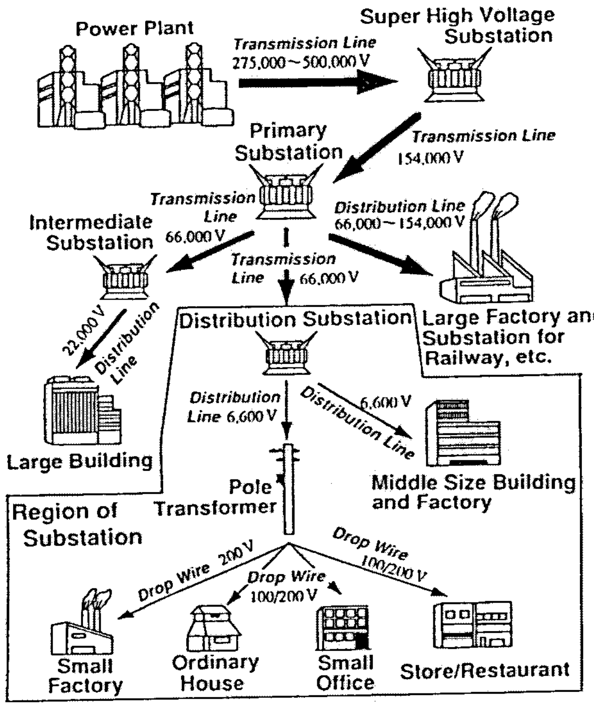

Figure 1 Electric Power Supply System

Table 1 Dates and Weather Conditions of Records

Season	Date	Weather	Temp. (Max.)	Humidity (Ave.)	Wind Velo. (Ave.)
Autumn	1991/10/16 (Wed.)	Cloudy and Occasionally Fine	21.1 ℃	54 %	2.7 m/s
Winter	1992/01/22 (Wed.)	Fine after Cloudy	11.7 ℃	45 %	2.3 m/s
Spring	1992/04/15 (Wed.)	Cloudy and Occasionally Fine	15.7 ℃	66 %	2.9 m/s
Summer	1992/08/19 (Wed.)	Fine	31.3 ℃	68 %	3.0 m/s

the effects of power outage on city life considering the distribution substation area having, for example, ordinary families, middle- and small-size offices, stores/restaurants and factories as one unit. The region of distribution substation, on which the lives of people in urban areas heavily depend is located at the bottom level of power supply systems (**Figure 1**).

2. Database of Power Demand and Areal Characteristics

To analyze the characteristics of power demand, we developed a database of power demand in the urban areas of Tokyo Metropolis. The database consists of coordinates of 314 distribution substations and their distribution areas (**Figure 2**), and hourly power demand recorded during the four seasons using geographic information system (GIS). In Japan, there are nine electric power supply companies. The Tokyo Electric Power Company, the largest private utility in the world, supplies power to the Kanto region of 39,497 km^2 which includes the 617.7 km^2 area under study. In 1992, the total power demand of the company was 230 x 10^6 MWh which was 33.8 and 82.1 % of Japan's and United Kingdom's total demand, respectively. The maximum peak demand in 1994 of the study area was 1.067 x 10^4 MW which was 18.4 % of the total maximum peak demand of the company.

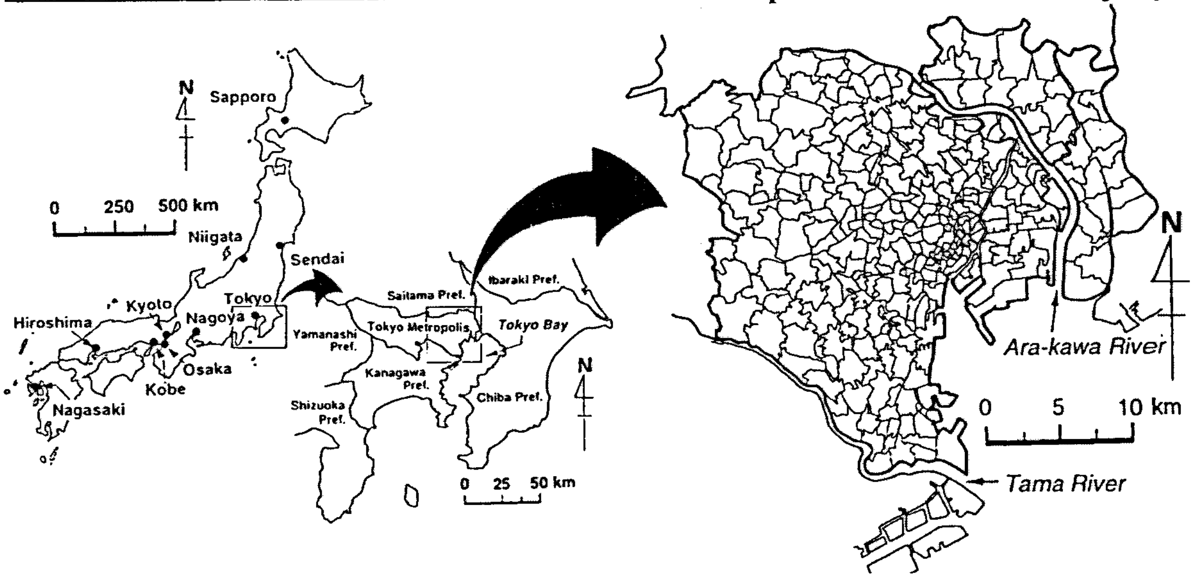

Figure 2 Map of Distribution Substation Areas in Study Areas (Urban Area of Tokyo Metropolis)

In general, considering the power demand and importance of the area, distribution substation area is assigned and one substation is installed in the area. Each substation has three transformers, each of which has a constant voltage of 6.6 kV. Although the power demand database of each substation consists of the voltage (V), current (A) and power (MWh) of the three transformers, we use the average current (A) of the three transformers as an index of power demand in this study since voltage changes of the transformers are very small (from a constant value of 6.6 kV). As a software of GIS, ARC/INFO of ESRI is used. **Table 1** shows the dates and weather conditions when the power demand was recorded.

Using ARC/INFO, we also developed a database of areal characteristics which were compiled from 500-m meshes. It consists of population and the numbers of families, offices, stores/restaurants and factories, etc.

3. Characteristics of Power Demand in Tokyo

Using the database of load curves of 314 distribution substations in the urban areas of Tokyo, we analyzed the characteristics of power demand in Tokyo from a macroscopic point of view. **Figure 3** is the power demand map in summer in which the darker the area is, the higher the power demand of the area becomes. The demand becomes minimum around 4:00 to 6:00. At about 8:00, the demand of the suburbs increases. Demand of the central office region and coastal industrial region of Tokyo increases at about 9:00. At around 14:00, suburb areas and the central region have high power demand because of the

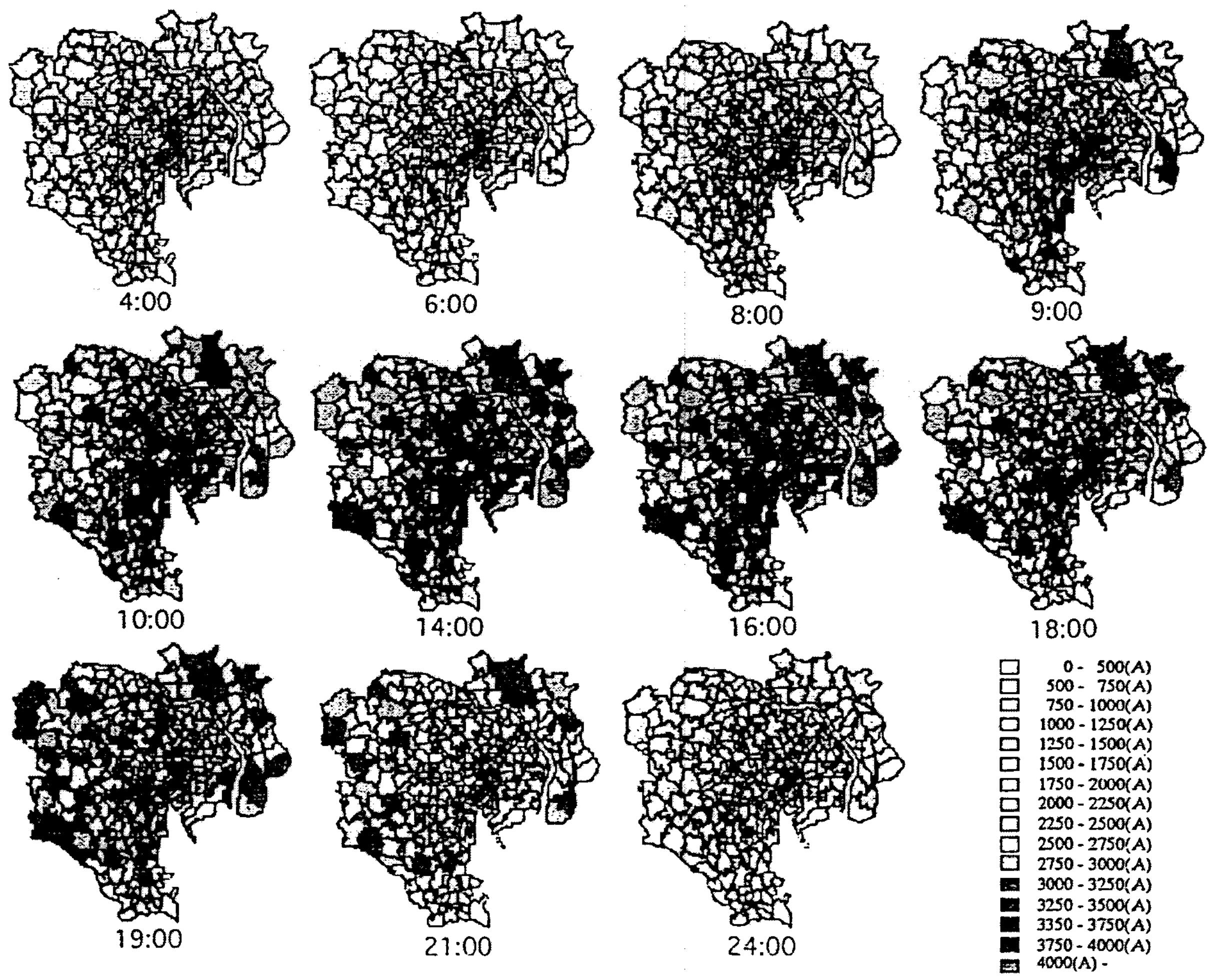

Figure 3 Power Demand Map of Tokyo Metropolis (Summer)

use of air conditioners. Power demand remains high till 18:00. From 19:00, however, we can clearly see that the areas having high demand are moving from the central to suburb residential areas.

To clarify the difference of areal characteristics based on power demand, we analyzed the load curves of each substation area. We found that in general, summer > winter > spring/autumn is the order of power load of each season, that there are several typical curves and that classification of the areas by such typical load curves might be possible.

The first type of load curves has a demand that increases at around 6:00 to 7:00 and remains a high level by about 23:00. Its most noticeable trend is the rapidly increasing demand during 18:00 to 19:00, when people go back to their houses, have dinner and relax as shown in **Figure 4-a**. This type of load curve is seen in residential areas of the suburb.

The second type shows that the load increases at 7:00-9:00 and decreases drastically at around 17:00 but is constantly high during daytime (**Figure 4-b**). The time with high load levels corresponds to the office working hours. This type of load curves can often be seen in the central areas of Tokyo where there are many office buildings.

The third one resembles the second type. However, the load becomes low for a short time during 12:00-13:00 as seen in **Figure 4-c**. This type of load curves is distributed around seaside or riverside in suburb areas of Tokyo where there are many small industrial companies. The low load at this time is due to the stopping of machinery during lunch time. The load curves after 18:00 resemble those of the first type because there are many buildings of small industrial companies which are also used as the owners' houses.

The fourth type shown in **Figure 4-d** has similar loads during daytime as those of office type but is different after 18:00. While the load of office type rapidly changes during 17:00-20:00 and decreases gradually after in a concave fashion, this type decreases in a convex fashion. This type of load curves is distributed in entertainment areas where there are many shops, restaurants, and pubs, etc., that are open from evening to midnight. Because these entertainment areas are often located near office areas in Tokyo, the load curves during

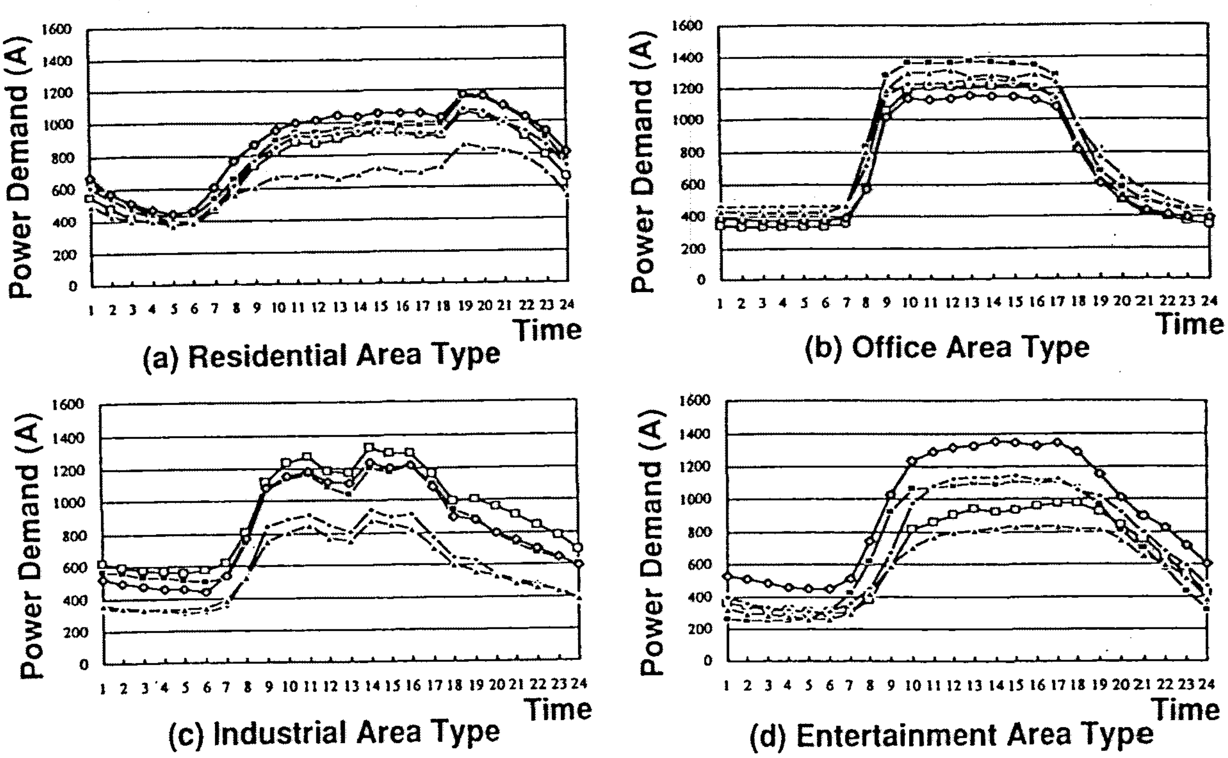

Figure 4 Characteristics of Typical Four Power Demand Curves (Summer)

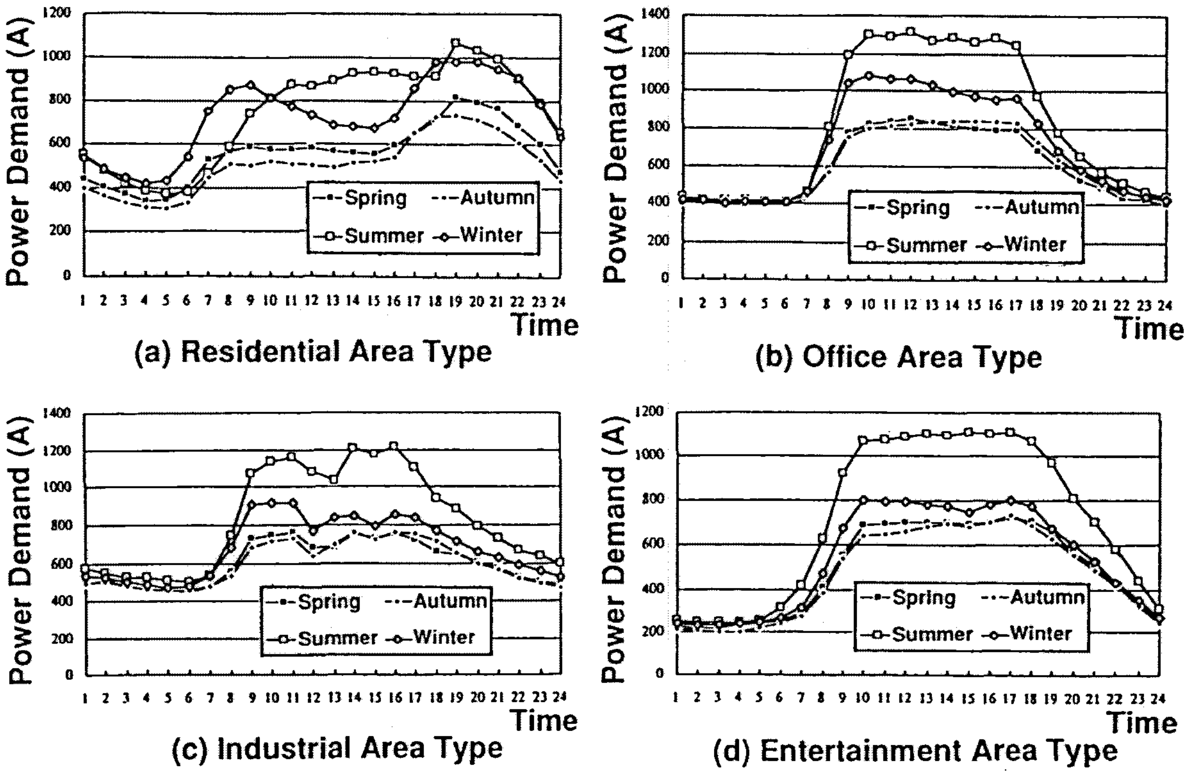

Figure 5 Seasonal Changes of Four Typical Load Curves

daytime are like those of the office areas.

The seasonal changes of each type of load curve are shown in **Figure 5**. Characteristics of the three load types related to business are common in all seasons although they have seasonal changes in their absolute amount (summer>winter>spring/autumn). In the residential type of load, there is a big difference between summer and winter. In summer, load is low in the morning and becomes high during the daytime due to the use of air conditioners. In contrast, because of the necessity of light and heater due to the short daytime and cold in winter, it becomes high from early morning. The first peak time occurs at around 8:00-9:00 when people are preparing and/or having breakfast and leaving. The load decreases during daytime with lower demand for lights and heater. It increases again with the second peak time coming at around 18:00-21:00 when lights and heater are again necessary as people go back home, relax and have dinner.

4. Calculation of Contribution Rate of Each Element Type

The areas introduced above are ones with typical load curves and can be classified into four typical types. Most other areas, however, are very difficult to classify into such four types. Even in typical areas, each area has the other three components, especially in the industrial and entertainment areas. Therefore, we considered that the power load of each area can be taken as a combination of these four typical types and tried to estimate the elemental four load curves (residential, office, industrial and entertainment) with a statistical technique.

Assuming that all load curves are expressed as the combination of four elemental load curves, load $y_j(t)$ at time t of distribution area j is expressed as

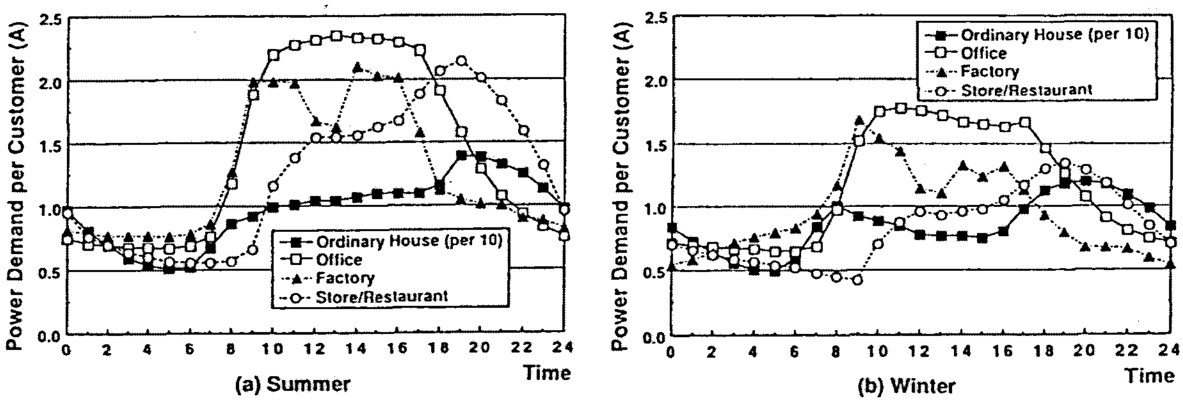

Figure 6 Calculated Four Elemental Load Curves per Customer

$$y_j(t)=\sum_{i=1}^{4}\alpha_{ji}\; x_i(t) \qquad (1)$$

where i shows four elements (i=1: residential, 2: office, 3: industrial, 4: entertainment), α_{ji} is the number of component i among j area, and $x_i(t)$ is an average load of the element i at time t.

If α_{ji} is given, optimal $x_i(t)$ can be calculated by multiple regression analysis. The power supply company, however, does not have α_{ji}; therefore, we calculated it for 150 substation areas excluding special small areas using the regional characteristic database introduced earlier. Data corresponding to polygonal area were transformed to obtain mesh data of regional characteristics and vice versa in proportion to the respective areas of the polygon and the grid. From the calculated α_{ji} of 150 areas, we obtained $x_i(t)$. Although load curves of residential, office and industrial components seemed to be good, that of entertainment component was bad. This can be due to a) that the number of stores and restaurants used here might have included many shops having office type business hours and b) that the areas in which there are many entertainment shops such as pubs and restaurants which open at night are rare and most have other characteristics such as shown in **Figure 4-d**. Therefore, out of 150 areas, we selected 80 areas in which there are very few entertainment shops. Among these 80 areas, and considering all the stores and restaurants as offices, we calculated the elemental power load curves of the residential, office, and industrial components. Applying these three elemental load curves to the areas in which there are many entertainment shops, we calculated the elemental load curve of the entertainment component. In this calculation, we assume that all the stores and restaurants are considered as nighttime shops.

Figure 6 shows the calculated elemental load curves in summer and winter. It is clearly seen that each curve has the same but stronger characteristic explained in **Figure 4**. The load curve of residential area has the highest seasonal difference. The load of every element in summer is higher than that in winter.

It is not proper to use the load curves shown in **Figure 6** to all areas because these curves are average curves among 80 areas in Tokyo Metropolis. For example, because the loads of large offices in the central Tokyo are much higher than those of small offices located in suburb residential areas, if the calculated office load curve is used in central areas, it leads to an underestimation; conversely, if it is adopted in suburb areas, it leads to an overestimation. When we analyzed the city characteristics from a macroscopic point of view considering 100 and/or 1,000 customers as a unit, load curves seem to be similar even if the size is different. From the shape of load curve, therefore, the characteristics of power demand are discussed hereafter.

5. Contribution Rate of Four Elemental Power Loads in Distribution Substation Areas

From the elemental load curves obtained earlier, contribution rates of all substation areas are calculated. **Figure 8** shows the flow of contribution rate calculation. All load curves, $y_j(t)$, of 314 substation areas are normalized by their maximum demand, y_{jmax}, expressed as

$$y_j(t)=y_j(t)/y_{jmax} \quad (2)$$

in which $y_{jmax}=y_j(T_j)$, T_j is the time of maximum demand.

Each elemental curve is normalized according to the method that the load at time T_j becomes one as

$$x_{ji}(t)=x_i(t)/x_i(T_j) \quad (3)$$

The normalized power load of area j at t, $y_j(t)$, can be expressed using four normalized elemental load curves, $x_{ji}(t)$, and their contribution rates C_{ji} as

$$y_j(t)=\sum_{i=1}^{4}\alpha_{ji}x_{ji}(t) \quad (4)$$

where $0 \le C_{ji} \le 1$, $\sum_{i=1}^{4} C_{ji}=1$.

Contribution rate of every area can be calculated by finding the combination of C_{ji} of each recording date which makes the value, Δy_j, a minimum:

$$\Delta y_j = \sum_{t=1}^{24}\{y_j(t) - \sum_{i=1}^{4}\alpha_{ji}\ x_{ji}(t)\}^2 \quad (5)$$

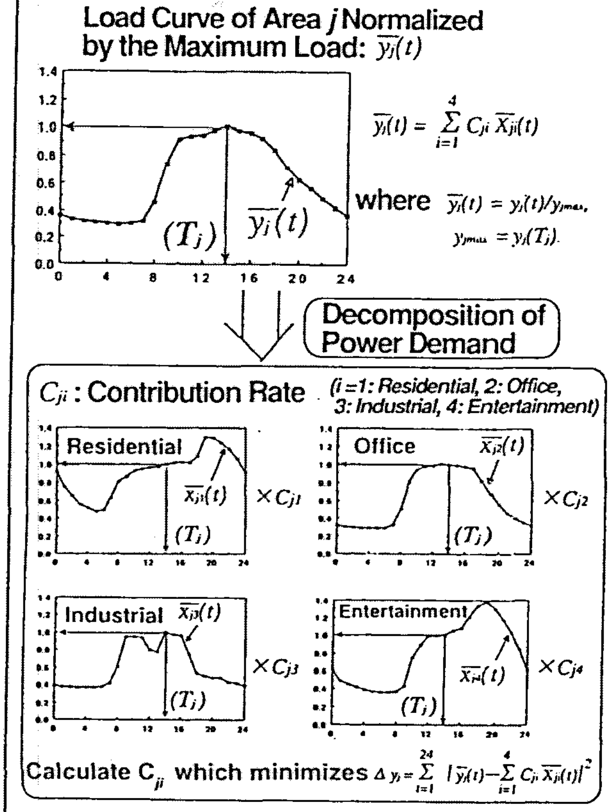

Figure 7 Flow of Calculation of Contribution Rates

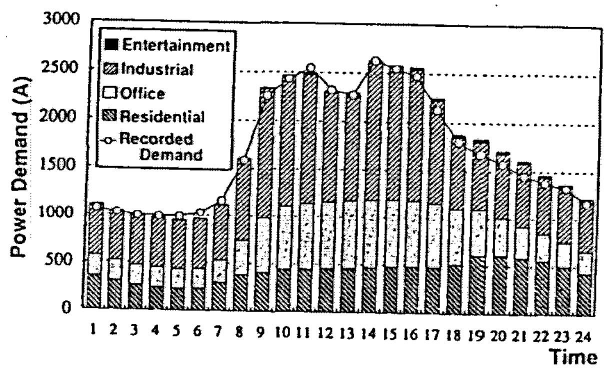

Figure 8 Comparison of Recorded Demand and Calculated Demand using Contribution Rates

Figure 8 shows the comparison of recorded power demand and demand calculated by contribution rate. From the resulting good agreement, it is clearly found that power load can be calculated using contribution rate. Contribution rate means the ratio of power used in residences, offices, factories, and restaurants/pubs, at peak-load time and is an index of the characteristics of power demand in an area.

Figure 9 shows the map of contribution rates of the four elemental demand. The areas with high rate of residence are located in suburb regions, especially in western Tokyo which is often called a residential area. The areas with high rate of office are located in the central part of Tokyo Metropolis. In the western part of Tokyo having high rate of residence, areas with high office rate are distributed along the railroads. The location of the areas with high factory rate is very limited along seaside and riverside and that of the areas having high entertainment rate is also very limited and its values are 40-50 % at the most.

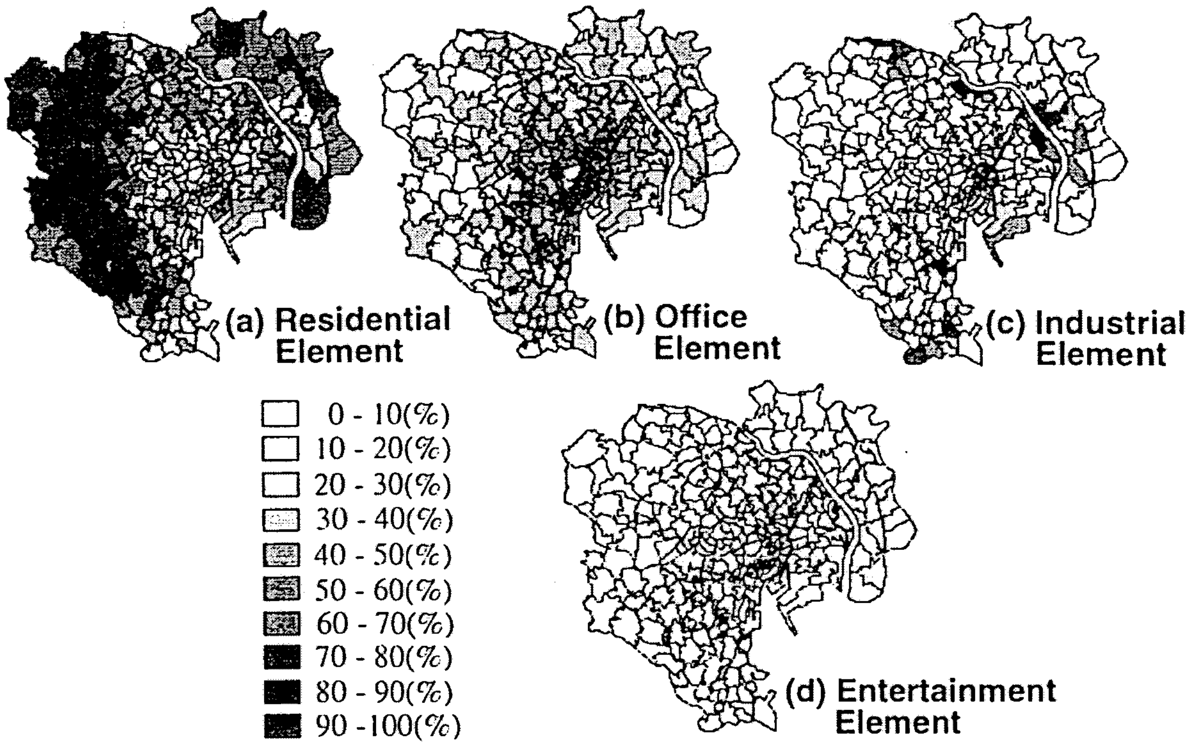

Figure 9 Map of Contribution Rates of Four Elemental Power Demand Components

6. Conclusions

We developed a database of power demand and areal characteristics in Tokyo Metropolis to investigate the effects of power outage in urban areas considering regional characteristics. From the study of the database, it is found that although power demand of a city area changes with time, season, and areal characteristics, it can be classified into four typical areas (residential, office, industrial, and entertainment) based on the shape of load curves. The pure four elemental load curves were calculated based on the assumption that every load curve is a combination of the four typical curves by multiple regression analysis. To estimate the areal characteristics from the power demand, the concept of "contribution rate" is introduced and calculated among 314 distribution substation areas. Using the contribution rate, we could classify the areas considering the characteristics of their load curves. The results show that this classification can be applied to estimation of the effects of power outage on various city functions considering the time and duration of outage, and the characteristics of the area. We will continue to study the effects of power outage by extending this study.

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