A Making method of Time-series energy demand data of non-residential buildings for urban energy analysis

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Abstract. Urban energy supply systems are changing to distributed energy supply systems according to the spreading of renewable energy. In order to effectively arrange and operate distributed energy supply systems in the city, it is necessary to (1) predict energy demands for each use in each building, (2) consider operation technology such as interchange or storage, and (3) study on a city scale rather than a building scale. Therefore, we aim to construct a method to calculate the optimal energy supply system with renewable energy based on data from geographical information systems (GIS). This paper describes the development of an energy-demand prediction method for non-residential buildings and a demand analysis in Japanese business areas by using this method. For the demand analysis, we developed a method to predict the demand of electricity and heat (heating, cooling and hot water) of non-residential buildings for one year. This program fluctuations in demand by five-minute intervals depending on the type of buildings (office, hospital, hotel, store, restaurant and school), total floor area, outdoor air temperature and so on. The standard demand amount of each type of buildings is based on statistical data and measurement data about energy consumption of non-residential buildings in Japan. Furthermore the fluctuation method of the demand incorporates random number simulation and probability distribution to reproduce an actual fluctuation. We predicted and accumulated the demand for hundreds of buildings by three districts for the demand analysis in the whole district. One of these analyses showed that there are large fluctuations in the demand of each building, and these fluctuations decrease by grouping the buildings in the block. Moreover, we analyzed the gap of peak demand between aggregated individual buildings and districts. This analysis revealed that some of peak demand in districts are less than 40% of aggregated individual.

1. Introduction

The urban energy supply systems are changing to distributed energy supply systems according to the spreading of renewable energy. In order to effectively arrange and operate distributed energy supply systems in the city, it is necessary to (1) predict energy demand for each use in each building, (2) consider operation technology such as interchange or storage, and (3) study on a city scale rather than a building scale. Therefore, we aim to construct a method to calculate the optimal energy supply system with renewable energy based on data from geographical information systems (GIS). While there were various studies [1-3] so far, these studies have confirmed some controversial points such as that the calculation time interval was large, the classification of types for non-residential buildings was few, or the target area was small. Therefore, this paper describes the development of the energy-
demand prediction method for non-residential buildings and the demand analysis in Japanese business areas by using this method.

2. Method for creating time-series energy demand data

The making method of time-series energy demand data was developed for six non-residential building types (hospital, hotel, office, store, restaurant, school). This method is a program that makes the individual demand of each building from the standard demand unit into five-minute intervals. This chapter describes the details of each procedure in the calculation flow of this program (Fig. 1).

![Figure 1. The calculation flow of this program](image)

2.1. Standard demand setting

At first, we made annual standard energy demand units and five-minute interval standard demand ratios for the standard of each of the six building types. We then used Japanese documents that described the standard energy demand of each building type in Japan to make the annual demand unit, and a five-minute interval demand ratio for the annual electricity demand units of the six building types. Table 1 shows the annual demand unit of the six building types. Figure 2 shows the five-minute interval demand ratios for the annual electricity demand unit of the six types of buildings in August as an example.

![Table 1. The annual demand unit](image)

| Annual demand unit | Office | Hospital | Store | Hotel | Restaurant | School |
|--------------------|--------|----------|-------|-------|------------|--------|
| Electricity[kWh/㎡]| 209    | 183      | 115   | 284   | 206        | 64     |
| Cooling[MJ/㎡]    | 363    | 366      | 295   | 627   | 432        | 246    |
| Heating[MJ/㎡]    | 162    | 200      | 55    | 188   | 322        | 67     |
| Hot water[MJ/㎡]  | 270    | 423      | 8     | 117   | 1,305      | 77     |

![Figure 2. The five-minute interval demand ratios for the annual electricity demand units of different types of buildings in August](image)
2.2. Annual demand changing
Annual demand changing and five-minute demand changing calculated from the standard annual energy demand unit and demand ratio based on the total floor area of the target building, the outside temperature, and usage schedule of the target building.

2.2.1. Annual demand changing by total floor area. Many factors affect the annual energy demand of buildings, but this paper focused on the total floor area of the building because this factor can be considered as the most important factor. We made natural logarithms of the annual demand units in each building type for the annual demand changing by total floor area based on statistical data about the energy consumption of non-residential buildings in Japan. Figure 3 shows those natural logarithms. We set equations of restaurant and school as a constant because there are few data and most restaurants have little floor area.

![Figure 3 The equation of annual demand changing by total floor area](image)

2.2.2. Annual demand changing by random number simulation. Even though two buildings has the same building type and the same total floor area, the annual energy demands of these buildings should be different in reality. Therefore, this paper also changes the standard annual demand unit by using random number simulation with a probability distribution in addition to the changing by total floor area, and makes the individual annual demand unit of each building.

We made frequency distribution for annual energy demand unit of each building type from statistical data about the energy consumption of non-residential buildings in Japan, and confirmed that the frequency distribution was the form as almost the same as the normal distribution when the number of data was enough. Therefore, we calculated the variances of normal distribution based on those statistical data, and made the normal distribution with those variances of each building type. We used these normal distributions as the change equation (equation (1)) for the annual demand unit of each building type by random number simulation. Table 2 shows the set variance. This program applies the random numbers made for each building to this equation and calculates the multiplication ratio for the annual demand of the building.

$$f(x) = \frac{1}{\sqrt{2\pi} \sigma^2} \exp\left[-\frac{(x - \mu)^2}{2\sigma^2}\right]$$

where $f(x)$ is probability density[-], $\pi$ is $\text{Pi}[-]$, and $\sigma^2$ is variance[-], $x$ is random variable(multiplication ratio for annual demand)[%], and $\mu$ is mean(=100) [%].
2.3. Five-minute demand changing

Five-minute demand changing makes the multiplication ratio of the energy demand ratio in five-minute intervals in each building.

2.3.1. Five-minute electricity demand changing by random number simulation. Changes in the behavior of people in a building are considered to have big effect to the fluctuation of the electricity demand. Therefore, we thought that the fluctuation of the electricity demand increases as the number of people increases, and then divided one day into four time zones by the number of people in the building. Table 3 shows the time zones. Random number simulation with normal distribution reproduced the change of the five-minute electricity demand due to changes in the behavior of people in a building by using different variances for each of the four time zones. We calculated the variance for each time zone from the measured data of one building (Table 4), and set normal distributions with these distributions as change equations of the five-minute electricity demand for each time zone. Moreover, time zones in one day are considered to differ by the building type. Therefore, this paper set four time zones for each building type from the standard demand ratio.

| Time Zone | Summary                                    |
|-----------|--------------------------------------------|
| Closing   | building is closing and there are few people |
| Start     | building opens and people come in          |
| Opening   | building is opening and there are many people |
| End       | building closes and people go out          |

Table 3. Time zones

Table 4. The variance for the equation of five-minute electricity demand changing

| Variance | Closing | Start | Opening | End |
|----------|---------|-------|---------|-----|
|          | 0.07    | 0.13  | 0.10    | 0.08|

2.3.2. Five-minute cooling and heating demand changing by outside temperature and random number simulation. Heat demand for cooling and heating is strongly influenced by outside temperature. In order to reproduce this influence, we made a change equation of the five-minute cooling / heating demand based on the outside temperature from the measurement data of two buildings. This equation calculates the multiplication ratio of the cooling or heating demand ratio in five-minute intervals according to the difference between the outside temperature at the target time and the monthly average value at the same time. Furthermore, this program reproduces the fluctuation of actual cooling and heating demand from calculating the fluctuation of these demand in the same outside temperature difference by using the random number simulation with the normal distribution. The variance of this normal distribution is the variance (= 0.14) calculated from the measured data. The equation of the five-minute cooling and heating demand changing by outside temperature and random number simulation is equation 2.

\[ y = (kx + 1) * \frac{R}{100} \]

where \( y \) is multiplication ratio of the cooling or heating demand ratio[\%], \( k \) is coefficient(cooling: 0.0647, heating: -0.0697)[ \(^\circ\mathrm{C} \cdot (-1)) \], \( x \) is difference between the outside
temperature and the monthly average value[°C], R is multiplication ratio by using the random number simulation with the normal distribution[%].

2.4. Demand calculation equations by energy application

Equations (3) - (5) show a summary of the calculation equations for the energy demands for electricity, cooling, heating and hot water in this method. The developed program calculates energy demand for each building in five-minute intervals by using these equations.

\[ E(t)_{El} = E_{Y_{El}} \cdot R(t)_{El} \cdot A \cdot C(A) \cdot R_y \cdot R_d \]  (3)

\[ E(t)_{Co,He} = E_{Y_{Co,He}} \cdot R(t)_{Co,He} \cdot A \cdot C(A) \cdot R_y \cdot R(temp) \]  (4)

\[ E(t)_{Hw} = E_{Y_{Hw}} \cdot R(t)_{Hw} \cdot A \cdot C(A) \cdot R_d \]  (5)

where \( E(t)_{El} \) is five-minute interval electricity demand [kWh/h], \( E(t)_{Co,He} \) is five-minute interval cooling or heating demand [MJ/h], \( E(t)_{Hw} \) is five-minute interval hot water demand [MJ/h], \( E_{Y_{El}} \) is annual standard electricity demand unit [kWh/h* m²], \( E_{Y_{Co,He}} \) is annual standard cooling or heating demand unit [MJ/h* m²], \( E_{Y_{Hw}} \) is annual standard hot water demand unit [MJ/h* m²], \( R(t)_{El} \) is five-minute interval standard electricity demand ratio [-], \( R(t)_{Co,He} \) is five-minute interval standard cooling or heating demand ratio [-], \( R(t)_{Hw} \) is five-minute interval standard hot water demand ratio [-].

\( A \) is total floor area [m²], \( C(A) \) is multiplication ratio for annual energy demand by total floor area [-], \( R_y \) is multiplication ratio for annual energy demand by random number simulation [-], \( R_d \) is multiplication ratio for five-minute electrical demand ratio by random number simulation [-].

3. Demand analysis in business areas by this program

This section calculated, analyzed and discussed the energy demand in Japan's three commercial and business areas by using our program. The demand calculation for these areas accumulated energy demand for each non-residential building in the target area.

3.1. Outline of demand calculation target area

Table 5 shows the number of buildings for each building type of the three areas and their total floor area. Tenjin area is the central business area of the city. Office and store buildings are concentrated in this area. Hakata station front area has many office buildings. And there are also many hotel buildings because this area is in front of the station. Daimyo area has many store buildings. The proportion of low-rise buildings is large in this area; thus, the sum of total floor space is small for the number of buildings.

| Area     | Office Number[-] | Hospital | Store | Hotel | Restaurant | School |
|----------|------------------|----------|-------|-------|------------|--------|
| Tenjin   | 249              | 8        | 260   | 1     | 31         | 4      |
|          | Total floor area [m²] | 897,826   | 32,359 | 1,211,352 | 10,477      | 7,321  | 5,288 |
| Hakata   | 255              | 6        | 151   | 31    | 32         | 13     |
| Station  | Total floor area [m²] | 572,463   | 13,100 | 602,753 | 210,227     | 6,654  | 42,127 |
| front    | Number[-]        | 174      | 1     | 224   | 7          | 29     | 4      |
| Daimyo   | Total floor area [m²] | 187,144   | 7,270  | 337,661 | 89,930      | 9,741  | 10,419 |

3.2. Analysis of fluctuation for five-minute energy demand in three areas

Figure 4(a)-4(d) show the demand in each of the three areas, and the demand of a general office building in Tenjin area, as a sample. The energy demand fluctuation of the three areas is calmer than that of the sample building in any energy application. The fluctuation trends of electricity demand in
the three areas are similar, these are almost constant after a sudden rising at approximately 9 o’clock (Start time zone), and return to midnight amount around 20 to 22 o’clock (End time zone). Cooling and heating demand have larger energy demand fluctuation of five-minutes than that of the electricity demand, because of the influence of the outside temperature. Hot-water demand has more peaks of the demand fluctuation than that of other energy usages. Tenjin and Hakata Station front areas have three peaks at 10, 13 and 18 o’clock, due to the characteristics of store building type. In addition, Hakata Station front area has a peak in hot-water demand for hotel even late at night. Heating and hot water demand in Daimyo area are smaller than those of the other two areas, due to the total floor area of the hospital building. This building type has a large heating and hot water demand.

3.3. **Analysis of demand diversity in each area**

This section analyses energy demand diversities by using a peak load ratio (PLR). In general, the peak demand in the whole area is smaller than the total amount of the peak demand of each building. Therefore, it is necessary to prepare supply systems with a capacity according to the peak demand of the entire area for high efficiency of regional energy supply. Thus, we calculated the PLR of each energy demand and indicated them as one of the standards for optimum energy supply. This paper takes the peak demand as the largest demand in the year.

Equation (6) shows the PLR [4]. The PLR takes a value from 0 to 1, and a value close to 1 indicates that there is a big divergence in the peak demand time of each building. On the other hand, a 0 value indicates that peak demand time for all buildings is the same time.

$$PLR = \frac{Q_{AISpeak load} - Q_{CSpeak load}}{Q_{AISpeak load}}$$  (6)

where $Q_{AISpeak load}$ is the sum of peak demand for each building[MWh/h or GJ/h], $Q_{CSpeak load}$ is peak amount of regional demand[MWh/h or GJ/h].

Table 6 shows PLR calculation result of each area by using the program. The difference of the PLR for electricity and cooling demand in the three regions is small. On the other hand, the PLR of heating and hot water demand is different because of the composition of building type in the area. The PLR of
the hot-water demand in Tenjin area is small; for this reason, there are few hotel buildings whose peak demand time of hot water are significantly different from those of other building types.

In addition, the PLR of the heating demand in three areas shows a high value of 0.4 - 0.5. This means that the sum of peak demand for each building is 40%-50% higher than the peak demand of the whole area. When introducing regional heating supply systems in such areas, setting the capacity to the sum of the peak demand of each building may be over-designed by 40%-50% of the actual required capacity.

Table 6. PLR of each area

|          | Electricity | Cooling | Heating | Hot water |
|----------|-------------|---------|---------|-----------|
| Tenjin   | 0.24        | 0.33    | 0.53    | 0.07      |
| Hakata Station front | 0.25 | 0.30 | 0.53 | 0.27 |
| Daimyo   | 0.26        | 0.34    | 0.41    | 0.19      |

4. Conclusion

In this paper, we developed the energy demand prediction method for non-residential buildings. Then, we calculated and analyzed the demand in Japanese business areas by using this method. As a result, it was confirmed that there are large fluctuations in demand for each building, and these fluctuations become smaller by grouping the buildings in the block. Moreover, the analysis of demand diversity revealed that some of the peak demands in districts are less than 40% of the aggregated individual. We set the Start time and End time for each building type as a fixed value in this report; however, these times should be different by each building and date even for the same building type. More detailed calculation requires these time zone variations. Moreover, in order to develop this research, we need to measure the area demand data for additional analysis such as accuracy verification.

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