APPLICATION OF ARCHETYPE ENGINEERING MODELING TO ESTIMATE HOURLY ELECTRICITY DEMAND OF COMMERCIAL SECTOR OF KEIHANSHIN METROPOLITAN AREA, JAPAN

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ABSTRACT

This paper presents an application of the archetype engineering modelling approach to the commercial building stock in the Keihanshin metropolitan area, Japan. This application especially focused on hourly electricity demand. The calculated peak electricity demand in August was estimated to be 11.1 GW and the time-varying characteristics was well modelled. However, the peak electricity demand was underestimated by 1.0 GW because not all building stock was covered in the model. Electricity demand during night was also underestimated by 1.5 GW, implied that more survey is needed on how people use commercial buildings and how building space and equipment is operated.

INTRODUCTION

Of the many urban-scale models developed in recent years for estimating the energy demand of building stocks, the most commonly used methodology is the archetype engineering modelling (Swan et al. 2010). The procedure of model development is described in the following steps: The building stock is divided into several stock categories according to the building characteristics and internal activities. An archetype model, representative of a particular building category, is then developed for all of the building stock categories. The unit energy demand for each category is next quantified by conducting building performance simulations by using the archetypes as input. Finally, the total energy demand is quantified by multiplying the unit energy demand by the number of units in each stock category.

There are two important features of the modelling approach. First, developed models reflect the structure in which energy demand is determined in buildings due to the second and third steps. Second, the energy performance of the entire building stock can be evaluated as the composition of building stock is taken into account in the first and forth steps. Due to this features, the developed models are capable of quantifying energy demand considering changes in technologies, climate and building stock.

Although there are a number of applications of the modelling approach, most of the applications only focused on yearly or monthly energy demand of building stock. Recently, however, a wide variety of energy management systems that control energy demand of buildings, such as demand response, has increasingly attracted attention because the building sector can provide changes in electricity demand that can improve economic, energy and environmental performance of electric power systems. In the energy management field, hourly or higher temporal resolution electricity demand is usually focused. For example, demand response to reduce peak electricity demand is implemented only within a few hours during which peak electricity demand is observed. However, the methodology to replicate time varying characteristics of energy demand in the archetype engineering modelling approach has not been well established.

Base on this background, this paper reports a preliminary modelling application to model hourly electricity demand of the commercial building stock in Keihanshin metropolitan area, Japan, in which 230 million m² of commercial buildings are located.

The remaining part of this paper reports each step of the model development procedure. Finally, we discuss some challenges to replicate hourly or higher temporal resolution energy demand by using the archetype engineering modelling approach.

CLASSIFICATION OF COMMERCIAL BUILDING STOCK

Building stock category

Yamaguchi et al. (2012) collected energy use intensity (EUI) data, which is defined as primary energy consumption per floor area, from approximately five thousands of retail facilities in Japan and found that the retail category, such as general merchandise stores, and food supermarkets, well explains differences in EUI. Based on the result, Matsuoka et al. (2013) proposed 14 building stock categories for the retail facilities in Japan according to the retail category and the size of facilities as listed in Table 1. Figure 1 shows the 95 % confident interval of the mean EUI of facilities in each retail stock category. The difference in EUI among the categories can be attributed to that retail facilities in each category has a certain trend in direct determinants of energy demand, such as the size, geometry of facility, the composition, specification and operation schedule of equipment and appliances.

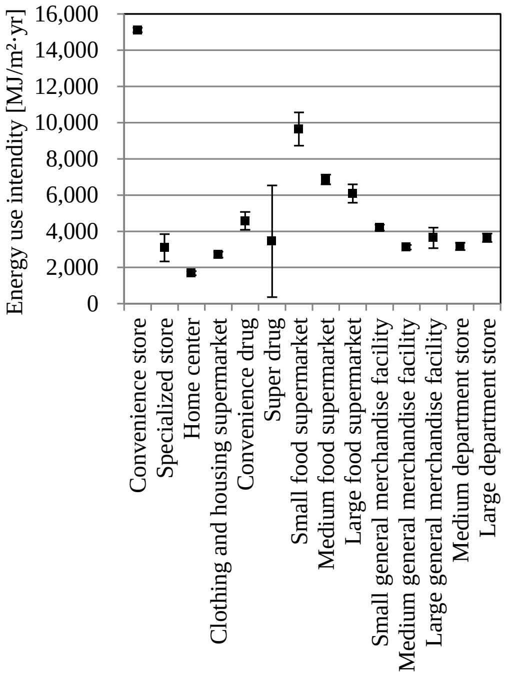

Figure 1. Average EUI of the retail stock categories

Table 1. Definitions of retail stock categories

Building stock category	**Sales area[m²]**
Convenience store	≥ 30 , < 250
Specialized store	< 250
Home center	≥ 250
Clothing and housing supermarket	≥ 250
Convenience drug	< 1,000
Super drug	≥ 1,000
Small food supermarket	< 1,000
Medium food supermarket	< 2,000
Large food supermarket	< 3,000
Small general merchandise facility	< 10,000
Medium general merchandise facility	< 30,000
Large general merchandise facility	≥ 30,000
Medium department store	< 30,000
Large department store	≥ 30,000

Similar approach was applied to the other commercial building usages, namely office, hotel, hospital/health clinic, education buildings, and restaurant/pub/cafe. Buildings involved in these usage categories were further classified according to the business category and the size of buildings. Table 2 lists the building stock categories considered in the model. In addition to the building usages, 9 classifications by building size were considered for office, hotel and hospital/health clinic. The reason why we considered building size is direct determinants of energy demand considerably vary with building size. The direct determinants are not only physical properties of buildings like geometry, but also operation hour of buildings, internal activities on floors, composition of HVAC systems and adoption of energy conservation measures.

Regarding the operation of buildings and internal activity on floors, we found the characteristics listed in Table 3 for each of building stock category.

Table 2. Building stock categories

Building usage	Business categories	Size and other attributes	
Office	General office	< 20,000 m²	
	General office, Compound office	≥ 20,000 m²	
Hotel	Commercial hotel	< 5,000 m²	
	Commercial, multi-function	≥ 5,000, < 20,000 m²	
	Multi-function hotel	≥ 20,000 m²	
Hospital/ Health clinic	Small medical office	< 1,000 m²	
	Middle scale medical office	≥ 1,000, < 5,000 m²	
	General hospital	≥ 5,000, < 20,000 m²	
	Large hospital	≥ 20,000 m²	
Education buildings	Primary school		
	Junior high school		
	High school		
	University 3 classifications by discipline & 4 by size	University/ liberal arts/ Science	< 1,000
			< 5,000
			< 10,000
			≥ 10,000
Restaurant/ Pub/Café (6 categories)	Restaurant	urban	
		suburban	
	Bar	urban	
		suburban	
	Café	urban	
		suburban	

Table 3. Characteristics in building operation and internal activity on floors

Building usage	Characteristics
Office	Operating hours increases with an increase in total floor area including Saturday and Sunday
Hotel	There are two kinds of hotels, namely commercial hotel for accommodation only and multi-functional hotel. With an increase in total floor area, the proportion of multi-functional hotel increases.
Hospital/ health clinic	EUI increases with an increase in building floor area. Small health clinic has small energy demand during night, while it is large in large hospital as medical facilities are operated. In addition to this, large hospital has a more space for advanced medical equipment, such as major surgery room, intensive care unit (ICU) and emergency room, with a high EUI.
Education buildings	EUI of elementary school, junior high school and high school is approximately 200 to 500 MJ/m² and that of university has a large variation according to the internal activities.
Restau-rant/ Pub/ Cafe	Kitchen area ratio of restaurants is larger than pub and café. In addition to this, operation hour is different among the categories.

Regarding the configuration of HVAC systems and adoption of energy conservation measures, we developed sub-categories as listed in Tables 4 and 5. Table 4 lists the considered classification of the configuration of HVAC systems, Table 5 does for energy conservation measures (Yamaguchi et al. 2010).

Quantification of total floor area of the building stock categories

Then, the total floor area of commercial buildings involved in each building stock category was quantified. Figure 2 shows the estimated total floor area of each stock category in the Keihanshin metropolitan area. For office, hotel, hospital/health clinic, we calculated the total floor area of stock based on the report on the property tax. For education building, we used a GIS data that contains usage, building coverage and height of individual buildings. For restaurant/pub/cafe, the business category and the address of approximately 100 thousands of restaurant/pub/café located in the metropolitan area was available. By using this data, we quantified the total floor area of restaurant, pub, and café respectively considering site locations with the distinction between urban and the other area, since restaurant/pub/cafe have different operation hours.

It should be noted that the total floor area was quantified for each prefecture in the metropolitan area, Osaka, Nara, Kyoto, Hyogo, Shiga and Wakayama, for which different meteorological condition was applied.

The estimated floor area for each stock category was further divided by the configuration of HVAC systems and the combination of energy conservation measures according to the adoption ratio.

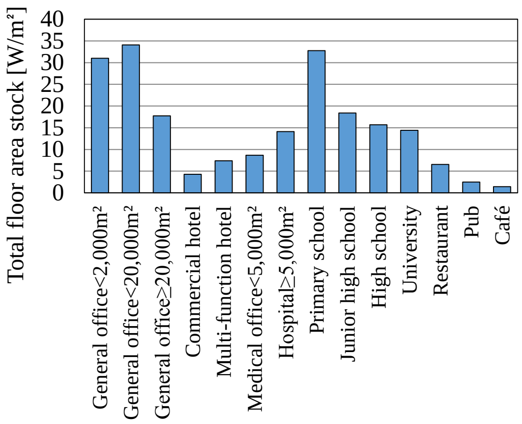

Figure 2. Estimated total floor area of each stock category

DEVELOPMENT OF BUILDING ARCHETYPES

The next step of the model development was the design of building archetypes for all of the building stock categories developed in the previous step.

To design building archetypes, we conducted surveys to collect information from available data sources on building attributes that have a significant impact on energy demand.

Building geometry and floor usage

Total floor area, floor plan, zoning, number of stories, floor usage were designed for each building archetype according to the dataset collected to quantify total floor area of each building stock category and some additional references so that the building archetypes represent each category. Table 6 lists the conditions given to the building archetypes.

Table 4. Composition of heat source system

System alternative	Heat source				Heat storage	CGS
	Cooling	Cooling COP	Heating	Heating COP		
CGS	Direct gas-fired absorption chiller	1.06	Same as cooling	0.83		Use
Heat storage	Air-cooling heat pump driven by electricity	3.05	Same as cooling	3.21	Use	
Ab	Direct gas-fired absorption chiller	1.06	Same as cooling	0.83		
Ab&Bo	Double effect absorption chiller driven by steam	1.06	Boiler	0.83		
Cc&Bo	Compression chiller	5.50	Boiler	0.83		
ACHP	Air-cooling heat pump driven by electricity	3.05	Same as cooling	3.21		
DisAC	Distributed air-conditioning system driven by electricity	2.77	Same as cooling	3.41		
GHP	Gas engine heat pump driven by city gas	0.95	Same as cooling	1.19		
Compound	It is adopted for both the heat source device which is powered with electricity and gas in heating and cooling either					

Table 5. Combination of energy conservation measures

	Level 1	Level 2	Level 3	Level 4	Level 5
Total enthalpy heat exchanger		○	○	○	○
VAV or VWV			○	○	○
Outdoor air cooling				○	○
Great difference of temperature conveyance					○

Table 6. Design of building archetypes

Building use	Attributes	CL1	CL2	CL3	CL4	CL5	CL6	CL7	CL8	CL9
Office	Total floor area [m^2]	132	349	726	1,447	3,258	7,089	13,873	31,238	190,202
	Building coverage [m^2]	66	116	182	289	543	1,013	1,734	2,840	6,559
	Number of stairs	2	3	4	5	6	7	8	11	29
	Floor usage	office							Office, Computation cabin, meeting room, restaurant, retail shop	
Hotel	Total floor area [m^2]	137	364	744	1,444	3,200	7,611	15,083	34,528	177,850
	Building coverage [m^2]	69	121	186	289	457	846	1,160	2,877	6,587
	Number of stairs	2	3	4	5	7	9	13	12	27
	Floor usage	Room clerk, lobby			Room clerk, Lobby, restaurant			Room clerk, Lobby, restaurant , banquet hall		
Hospital /Health clinic	Total floor area [m^2]	136	330	701	1,455	3,238	7,597	14,696	31,309	104,835
	Building coverage [m^2]	68	110	234	364	648	1,266	2,449	4,473	6,989
	Number of stairs	2	3	3	4	5	6	6	7	15
	Floor usage	Clinic, waiting room, lobby, inspection office			Clinic, waiting room, lobby, inspection office, bedroom		Clinic, waiting room, lobby, inspection office, bedroom, operating room		Clinic, waiting room, lobby, operating room, ICU, inspection office, bedroom	
Elemen-tary, Junior high, & High school	Total floor area [m^2]	3,000			1,500			Note: we assumed that elementary school, junior high school and high school consist of two buildings listed on the left.		
	Building coverage [m^2]	1,000			500					
	Number of stairs	3			3					
	Floor usage	Classroom, special classroom, management room			Classroom, special classroom, management room					
Univer-sity	Total floor area [m^2]	5,775								
	Building coverage [m^2]	1,155								
	Number of stairs	5								
	Floor usage	Liberal arts laboratory, physical science laboratory, lecture hall, server rom, office								
Restau-rant/Pub /Cafe	Total floor area [m^2]	150							Note: we assumed one building geometry for all of the restaurant/pub/café.	
	Building coverage [m^2]	150								
	Number of stairs	1								
	Floor usage	Restaurant customer seat, restaurant kitchen, bar customer seat, bar kitchen, café customer seat, café kitchen								

Table 7. Setting of internal activity

Building use	Floor usage	Lighting [W/m²]	Appliance [W/ m²]	Occupants [person/m²]	Quantity of outdoor air intake [m³/(m²·h)]
Office	Office room	12	12	0.1	5
	Computation cabin	4	500	0	0
	Meeting room	10	2	0.25	5
Hotel	Room clerk	15	4	0.07	4
	Lobby	20	5.2	0.1	2.5
	Banquet hall	50	0.5	0.7	5
Hospital/health clinic	Clinic	20	15	0.2	5
	Waiting room/lobby	6.7	10	0.1	6
	Inspection office	20	30	0.1	6
	Operating room	60	50	0.15	6
	Sickroom	12	3	0.08	4
	ICU	20	30	0.1	4
Education	classroom	8.0	0.2	0.45	0
	Special classroom	8.0	0.2	0.45	0
	Management rooms	8.0	11	0.10	5
	Liberal arts laboratory	8.0	5.5	0.1	3.0
	Physical science laboratory	8.0	11.5	0.1	3.0
	Lecture hall	8.0	2	0.3	0.0
Restaurant/pub/ cafe	Restaurant customer seat	30	30	0.5	5.0
	Restaurant kitchen	15	50	0.1	12.5
	Pub customer seat	25	30	0.5	5.0
	Pub kitchen	15	50	0.1	12.5
	Café customer seat	30	30	0.4	5.0
	Café kitchen	15	33	0.1	12.5

Setting of occupants, lighting, appliance and ventilation

Each floor usage has specific conditions on the density of occupants, lighting intensity, appliance intensity, volume of outdoor intake. Each of the item is modelled by the maximum value and operation schedule. The setting of the intensity is shown in Table 7.

We assumed the schedule of occupants for each floor usage based on available sources. Figure 3 shows a result of the setting, the occupant intensity of the archetype buildings on weekdays. We assumed that lighting and HVAC systems are operated while one or more occupants is using the floor. Appliances whose usage is shared by a number of occupants, the same operation setting was applied. For appliances that is used personally, the operation schedule is assumed to be same as the occupancy schedule. Finally, for appliances that usage do not vary with time, a constant consumption is assumed over time.

Electricity demand for building management

In addition to electricity demand corresponding to the activity of occupants, we assumed miscellaneous electricity demand for building management like those for elevator, water pumping and equipment for sanitary, emergency and security. To design the intensity and schedule of the miscellaneous demand, we analyzed hourly electricity demand of 17 office buildings for which the composition of electricity demand by end-uses was available. The data showed that 3.1 W/m² of electricity was always consumed on average independently from occupants' activity in buildings. Occupants' activity in buildings accompanied 4.0 W/m² of electricity that varies with the occupancy rate in buildings. Based on the result, the miscellaneous electricity demand was assumed to be 7.1 W/m² and in it 4.0 W/m² of electricity varies accordingly to the occupancy rate of buildings.

This is the setting for office buildings. For the other usages, such electricity demand data was not available. Instead, we adjusted the electricity intensity corresponding to the 3.1 W/m² and 4.0 W/m² according to the specification of building equipment. According to building equipment data collected from 421 office buildings showed that the electric capacity for miscellaneous load is 24.5 W/m² for emergency and security equipment, while 15.5 W/m² for sanitary, elevator lifting transport. These values can be calculated for the other building usages. Thus, we assumed that 3.1 W/m² of the miscellaneous demand that is constant over time corresponds to the capacity of the emergency and security equipment, while 4.0 W/m² that varies with the occupancy rate does to the capacity of the equipment for sanitary, elevator lifting transport. Based on the assumption, the electric capacity of miscellaneous demand was decided as to be proportionate to the ratio of the capacity between office and the other usage.

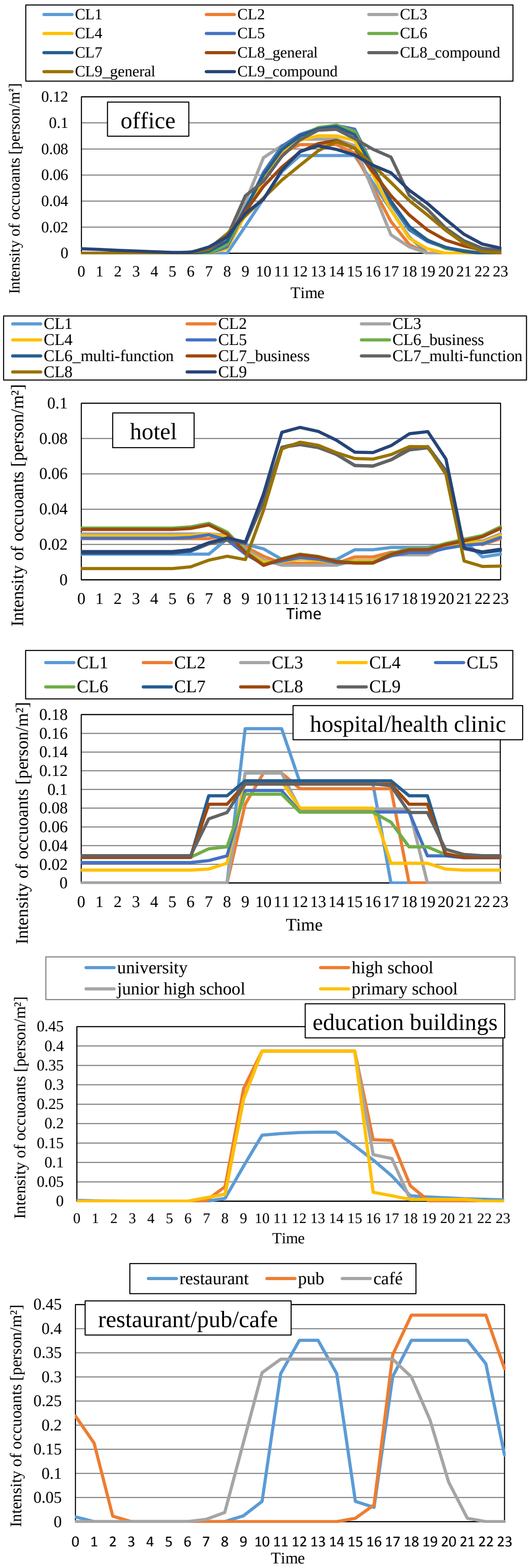

Figure 3. Estimated intensity of occupants of the building archetypes on weekdays

ESTIMATION OF UNIT ENERGY DEMAND

Simulation model

The developed building archetypes were used as input datasets for estimating EUI of each stock category.

Figure 4 shows the model used to estimate energy demand. The model calculates end-use energy demand and corresponding energy consumption for heating, cooling, ventilation, lighting, refrigeration and other (Yamaguchi et al. 2010). The minimum unit for simulation was one building floor. To estimate heating and cooling demands of a floor, thermodynamic and HVAC system simulations were performed on an hourly basis. For the simulation of electricity usage, the capacity and schedule assumed in the building archetypes were given. For refrigeration systems, the thermal load of refrigeration cabinets was estimated while considering air leakage from the cabinet and the internal heat gain from display lighting. By using a regression model of the relationship between thermal load and energy consumption, the energy consumption was quantified (Suzuki et al. 2011).

Hourly electricity demand of each building stock category

Figure 5 shows the estimated mean hourly electricity demand per floor area on weekdays in August in 2010 with the meteorological conditions for Osaka. Here, we assumed DisAC (see Table 4), electricity driven heat pump system, in the archetype buildings to clarify the variety in energy demand among the building stock categories. Corresponding to the setting in the building archetypes, each building stock category showed different hourly electricity demand. For example, office, hotel and hospitals/health clinics showed an increase in electricity demand with an increase in the total floor area due to longer operation hours of buildings corresponding to the mix of floor usages.

Hourly electricity demand of each HVAC system configuration

In addition to building stock category, the configuration of HVAC systems have a significant impact on hourly electricity demand. Figure 6 shows the mean hourly electricity demand of the office archetype whose total floor area is larger than 5,000 m² to 10,000 m². As shown in the figure, hourly demand profile differs significantly according to the configuration of HVAC systems. The archetype buildings using heat source systems driven by gas (CGS, Ab, Ab&Bo, GHP) has a smaller electricity demand compared to those using heat source systems driven by electricity. Buildings using a thermal storage system (Heat storage) has a high electricity demand during night.

As mentioned earlier, the share of these HVAC system configuration is taken into account in the fourth step, which enables estimated energy demand to reflect the accumulation of HVAC systems in the building stock.

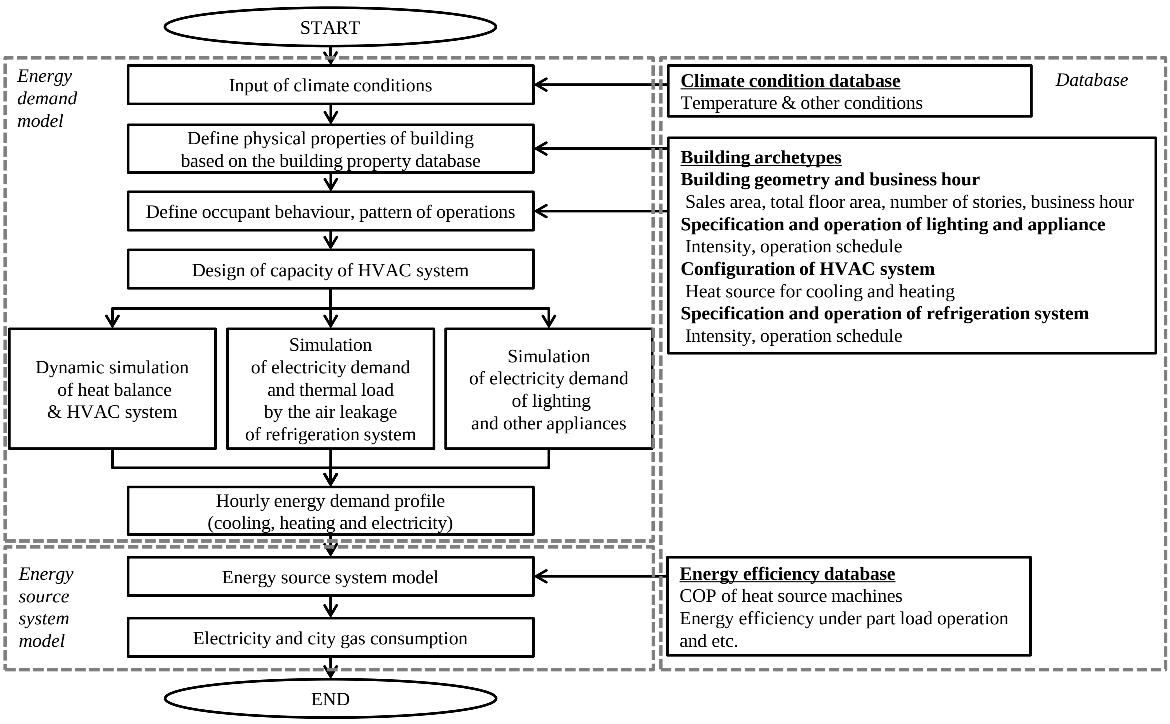

Figure 4. Simulation procedure and databases for models used in this study

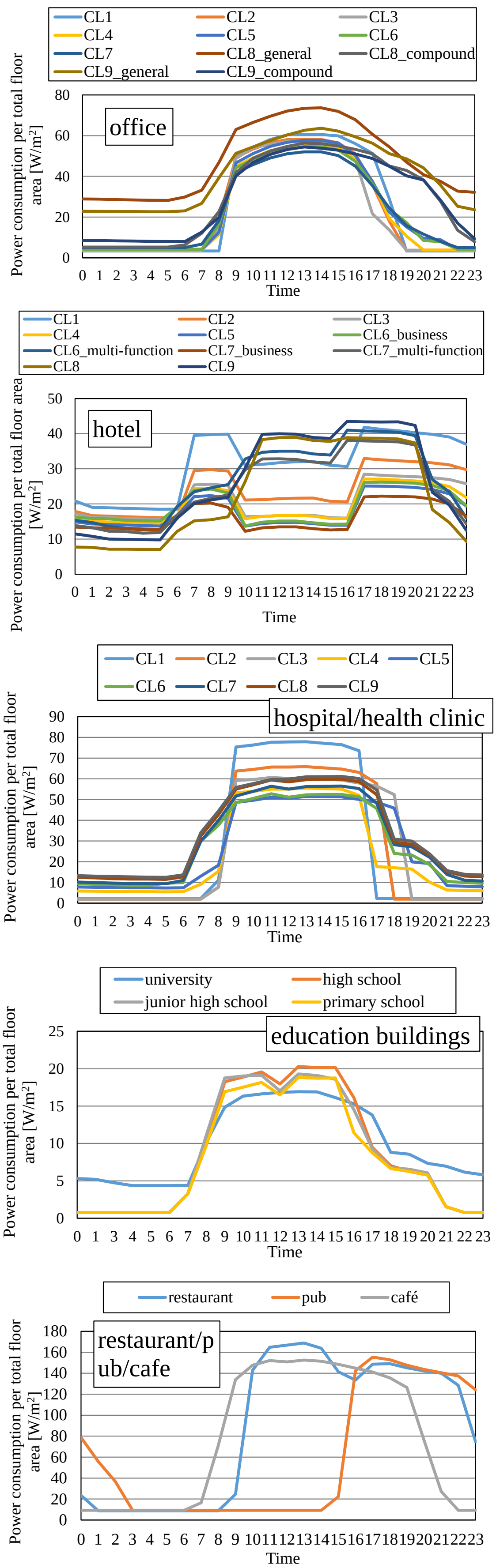

Figure 5. Mean hourly electricity demand on weekends in August with DisAC

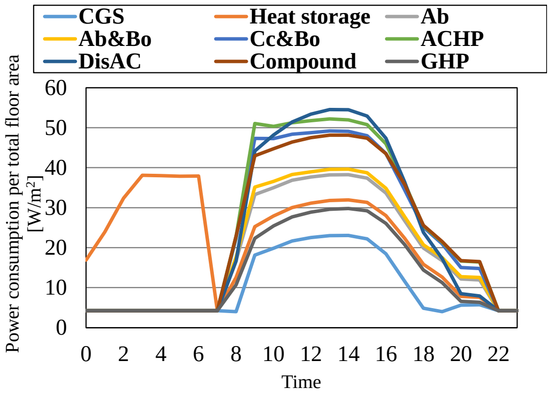

Figure 6. Mean hourly electricity demand on weekends in August of the office CL6 (≥5,000 , <10,000 [m²])

AGGREGATION OF ENERGY DEMAND

The total energy demand of the entirety of the commercial sector of the Keihanshin metropolitan area was quantified by aggregating the estimated total energy demand of all of the building stock categories.

Simulation result of hourly electricity demand

The total energy demand of each stock category was calculated by multiplying the total floor area with hourly electricity demand per floor area. Figure 7 shows the total hourly electricity demand for weekends in August 2 on which there is a peak electricity demand. Red line in figure 7 shows measured value. The estimated peak electricity demand is smaller by 1 GW for 12 GW of the actual peak demand, while it is also 1.5 GW smaller for 3.5 GW of night time demand.

Figure 7 showed that although the developed model underestimated the total electricity demand, the shape of the demand well agreed with the actual electricity demand.

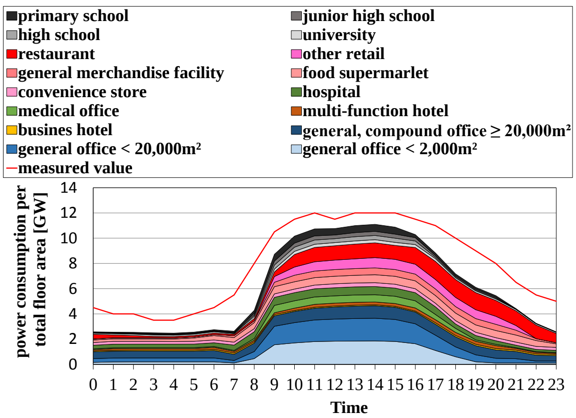

Figure 7, Mean hourly electricity demand of weekends in August

DISCUSSION

Due to the features of the archetype engineering modelling approach, the developed model is capable of quantifying energy demand while reflecting the structure determining energy demand in buildings as well as the composition of building stock. This result shown in Figure 7 implies that models developed based on the archetype engineering approach is capable of modelling the time-varying characteristic in energy demand. The classification of buildings stock according to the business category and the size of commercial buildings together with the design of building archetypes for each building stock category played important role to decide the time varying characteristic in the simulation result.

However, the underestimation of electricity demand revealed a typical weakness of bottom-up energy demand models. The underestimation can be attributed to that the entirety of the commercial building stock was not fully covered. The developed model only covered main building usages for which sufficient data was available. The available data for other usages is insufficient to classify buildings to capture the diversity and to develop building archetypes representing building stock.

In addition to this problem, electricity demand during night was significantly underestimated. The error observed was about 1.5 GW. The relative error is much larger than the peak time. There are two challenges to overcome the observed error. First, the number of occupants using commercial buildings during off-peak time must be understood including night time. For example, our assumption of office building shown in Figure 3 was that less occupants are using building after mid-night. However, there are many buildings operated during night. We ignored it since we did not consider operational characteristics in the classification of building stock. To overcome this challenge, building stock categories representing such buildings must be developed. Urban scale transportation data might be a good source to check the appropriateness of the setting in occupancy. The second challenge is to understand operation of appliance and equipment more correctly. There are many appliance and equipment whose operation and energy consumption are not proportional to the number of occupants using buildings. Understanding on this point would be also beneficial to find flexibility in energy demand to be used to improve electric power systems.

It should be noted that each of representative model has a different weight in the total energy demand according to the total floor area of building stock categories. Thus, unnatural discontinuous change can be generated in estimated energy demand when a small number of building stock categories have a large amount of total floor area. This weakness implies another challenge that the building stock category should be developed so that each representative building model has same total floor area to represent building stock so that building stock category is developed based on the impact on the total energy demand, instead of based on available data on building stock. The difference in the buildings' operation condition would be the most important factor to be considered. Another potential approach is to adopt statistical approach assuming statistical distribution in buildings' operation conditions. It is attractive even when building stock category was developed based available data on building stock, if such statistical information and rich computational power are available.

CONCLUSION

This paper presented an application of the archetype engineering modelling approach to the commercial sector building stock in the Keihanshin metropolitan area in Japan to estimate hourly resolution electricity demand. The model is capable of evaluating potential change in energy demand due to changes in technologies, climate and building stock. In the model, we classified commercial buildings into 2,925 building stock category by considering business category, building size, and configuration of HVAC systems and adoption of energy conservation measures. The calculated peak electricity demand on weekdays in August was 11.1 GW which was lower than the actual electricity demand by 1.0 GW. Off-peak time demand was also underestimated. Based on the result, we discussed challenges to reflect the time-varying characteristic in energy demand of commercial buildings by using the archetype engineering modelling approach.

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