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DATABASE AND SIMULATION MODEL DEVELOPMENT FOR MODELLING THE ENERGY USE OF NON-RESIDENTIAL BUILDINGS

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ABSTRACT

This paper discusses modelling methodology of the energy use of a certain amount of building stock at the city/regional/national level. In the methodology, building stock is divided into several stock categories and unit energy consumption for each category is quantified by performing simulations using prototypical building models as simulation input each representing a building stock category. For accurately modelling the energy use and estimate potential contributions of energy-conservation technologies, classification of the building stock is crucial as it homogenizes the stock group. This paper quantitatively evaluates how classification of building stock according to a number of building properties improves the accuracy of simulation model.

INTRODUCTION

There have been a number of studies that estimate the energy consumption and carbon dioxide emissions from a certain amount of building stock at the city/regional/national level by applying the methodology consisting of the following four steps:

1) Classifying the whole building stock into several categories according to the characteristics in terms of the energy consumption;
2) Designing building prototypes, each representing a building stock category which is used as input dataset for simulation in the next step;
3) Performing simulations using these prototypical building models in order to predict the energy consumption per unit floor area or household in each building stock category;
4) Aggregating the total energy consumption by summing up the predicted energy consumption of all the building stock categories.

This methodology is called "Average Dwelling Method" in Europe when it is applied to the residential buildings (Nataraja et al., 2007). This modelling approach is useful as the previous models have demonstrated. For example, Petersdorff et al (2006) estimated the potential reduction of carbon dioxide emissions that would be delivered by the implementation of the EU Directive on the Energy Performance of Buildings (EPBD) and the enhancement of the directive.

While there are an increasing number of its applications (Haung et al. 1991, Shorrock et al. 1997, Natarajan et al. 2007, Petersdorff et al. 2006, Boardman 2007), it has not been well discussed whether the methodology assures the accuracy of the simulation result.

The simulation error potentially arises from the three areas. The first area is simulation-software used in the third step to determine the unit energy consumption per floor area for each stock category. An accurate simulation-software delivers an accurate relationship between input parameters and simulation outputs. This error can be avoided by selecting proper simulation-software for the process.

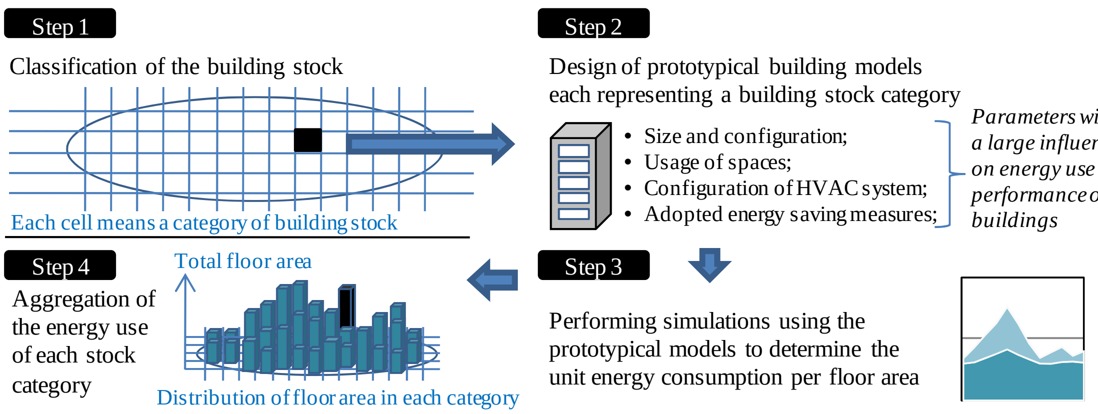

Figure 1. Procedure to develop a model of energy use in a certain amount of building stock

The second area of error is prototypical building models designed in the second step. Prototypical building models are designed according to a number of selected parameters that determine the characteristic of energy consumption in buildings. The parameters must be selected in order of the impact on the simulation results instead of data availability while it is usually so. Thus, it is important to clarify how classification of building stock according to the selected parameters addressed in the prototypical building models contributes to improving the accuracy of the simulation model.

The third area of error is the distribution of floor area in each building stock category, which is given the distribution of the selected parameters.

The paper especially focuses on the second area. Authors have developed a model predicting the energy demand of the commercial sector of Osaka city, Japan, by following the procedure shown in Figure 1. We have validated the simulation-software that is used in the third step (Yamaguchi et al. 2004). We also compared the simulation result of annual total electricity and city gas consumption with the statistic data to validate the database developed for selected parameters to address the third error area. The demand for electricity and city gas estimated by the model shows a good agreement with the statistic data. However, the second error area has not been evaluated. The purpose of this paper is, thus, to address this error area. We quantitatively evaluate how classification of building stock according to selected parameters in the modelling procedure would contribute to improving the accuracy of the simulation model.

In this paper, we first introduce the model for the commercial sector of the Osaka city. We then describe the methodology and result of evaluation. We finally derive some implications to improve modelling methodology for estimating energy use of a certain amount of building stock.

ENERGY DEMAND MODEL OF THE COMMERCIAL SECTOR OF OSAKA CITY

This section introduces the energy demand model of the commercial sector of Osaka city, Japan. This model is designed to evaluate the extent to which a variety of energy-conservation measures and energy management methods would contribute to carbon dioxide emissions reduction. The intended user is the city government who is looking for pathways to a low-carbon society. Energy utility companies are also a potential user as the model is able to analyze the relationship between the energy demand and specific changes in elements of energy system. To contribute to these users, it is important to grasp the general characteristic of the majority of building stock. The modelling approach is appropriate, as the developed model is capable of quantifying the total energy demand while considering the variety in elements that have a considerable influence on the energy consumption of buildings.

Classification of building stock

The characteristic of energy use varies significantly among buildings due to:

- Size and configuration (e.g. shape and zoning) of buildings, which affect the thermodynamic characteristics of buildings;
- Usage of spaces in buildings, which determines the scale and pattern of heat gains and electricity loads from spaces and operation hours of HVAC systems;
- Configuration of HVAC system;
- Adopted energy-conservation measures;

In order to take into account the influence of these parameters in the prediction of energy use, we classified the building stock into 36000 categories by parameters shown in Figure 2. In the model, we divided the building stock in each principal usage into five size ranges. Classification according to the configuration of HVAC system, energy-conservation measures is explained later.

Design of prototypical building models

We designed prototypical building models for each building category. Common values are given for the parameters other than the selected parameters. We also developed databases to model the distribution of these parameters used in the fourth step explained in Figure 1.

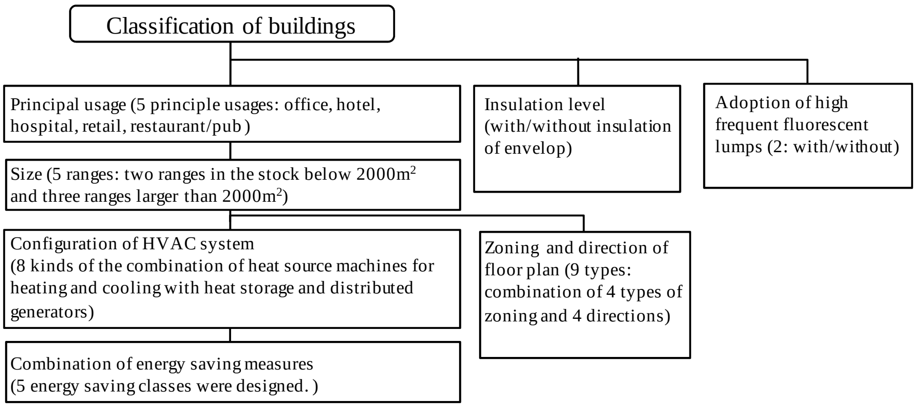

Figure 2. Classification of buildings

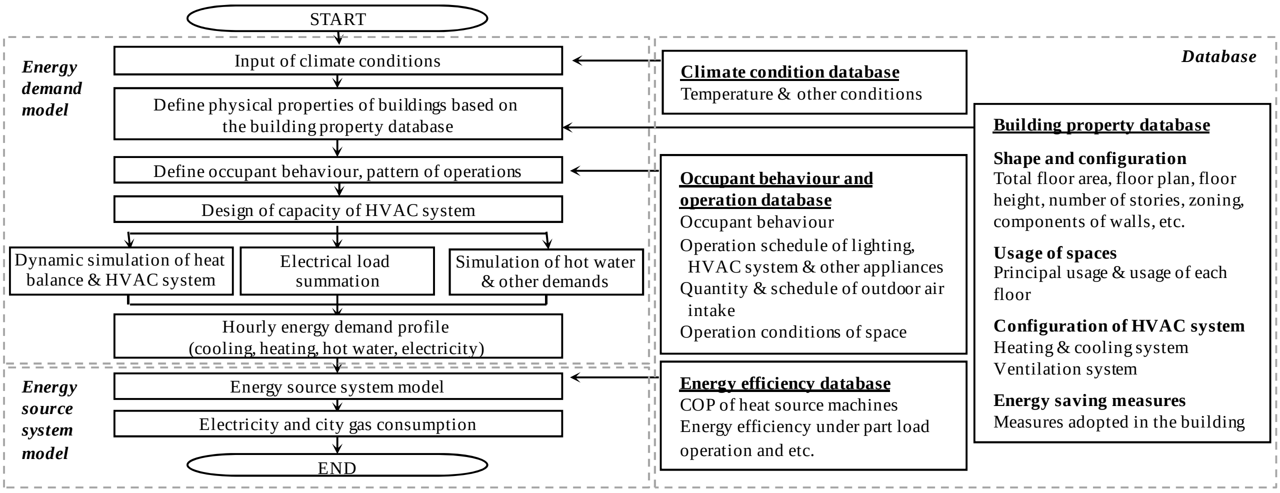

Figure 3. Simulation procedure and databases

Simulation-software

Figure 3 illustrates the simulation procedure to predict the energy use of prototypical buildings.

This model can be divided into two sub-models——the building energy demand model and the energy source system model——and four databases: the occupant behaviour and operation database, building property database, climate condition database and energy efficiency database. The occupant behaviour and operation database contains information on occupant behaviour, operation schedule of lighting, air-conditioning system, and other appliances (e.g. office equipments) for each space usage. The building property database contains information on the building properties given by the prototypical building models. The climate conditions are given by the climate condition database. The energy efficiency database contains information on the energy efficiency of appliances and heat source machines.

In the building energy demand model, the heating, cooling, hot water and electricity demand profile is simulated on an hourly basis. The energy source system model determines the energy use (electricity and city gas) for satisfying heating, cooling and hot water demand. The total electricity demand is determined by summing up all the electricity uses.

Due to the structure, the energy demand profile and total energy consumption that are calculated for each prototypical building models involves the influence of climate conditions, building properties, occupant behaviour, configuration and operation of HVAC systems, and efficiency of appliances and machines. A detailed explanation of this model is given elsewhere (Yamaguchi et al. 2003).

Aggregation of the total energy consumption

The energy consumption per unit floor area is determined for each building stock category by dividing the energy consumption estimated for each prototypical building model by its total floor area. The total energy consumption of the whole building stock is then determined by summing up the energy consumption of all the building stock categories given by multiplying the unit consumption and the total floor area in each building stock category.

Method of classification building stock and consideration of the configuration of HVAC system, energy-conservation measures and space usage

Here we explain method of classification of building stock according to the configuration of HVAC system, the adoption of energy-conservation measures and the usage of spaces.

1) Configuration of HVAC system

We analyzed a database in which HVAC systems that equipped in newly constructed buildings from 1983 to 2006. We specified eight kinds of HVAC systems from the analysis. The selected HVAC system occupies more than 95% of the sample. Prototypical building models were designed with each HVAC system. The result is then averaged using the share of each HVAC system as the weight.

2) Energy-conservation measures

We also analyzed the abovementioned database on newly constructed buildings for analyzing share of the combination of energy-conservation measures. In the analysis, we first divided the building stock according to the building size range, principal usage and kinds of HVAC system (central HVAC system or distributed system) in order to take into account the difference in the distribution of energy-conservation measures. We then designed five classes on the combination of energy-conservation measures for each building stock category. Buildings in the first class assumes no energy-conservation measures adopted. Buildings in the second class are assumed to equip an energy-conservation measure that currently has the highest adoption ratio. The energy-conservation measures assumed in each class gradually increase with the increase in the class, as buildings in fifth class are assumed to equip all available energy-conservation measures considered in this study. We also determined the share of each energy-conservation class to apply it in the fourth procedure shown in Figure 1.

3) Usage of spaces

The database on newly constructed buildings contains information of space usage in terms of floor area. By using this database, we specified the share of space usage in the total floor area for each size range of each principal usage. Although we designed the usage of each floor of prototypical building models based on the distribution of space usages, we did not classify the stock according to the space usage.

METHODOLOGY OF EVALUATION

As explained in the previous section, the building stock is classified according to the configuration of HVAC system, the adoption of energy-conservation measures. In this section, we explain the methodology employed to evaluate how the classification of the building stock would contributes to improving the simulation accuracy.

We carried out a questionnaire to owners and managers of office buildings to investigate monthly energy consumption (electricity and city gas) from April 2007 to March 2008 as well as configuration of HVAC system and energy-conservation measures implemented in their buildings. We got 31 valid returns. We investigated the buildings and developed the database of information listed in Table 1.

By fully applying the database to the same simulation-software used in the Osaka city model, we predict the total monthly consumption of electricity and city gas. We also predict the energy consumption with different datasets explained below assuming different modelling approaches are applied to model the energy use of the buildings. By comparing the measured and predicted energy consumptions, we evaluate how the simulation result is affected by modelling approaches. In addition to monthly electricity and city gas consumption, we compare potential carbon dioxide emission reduction gained by fully disseminating several energy-conservation measures.

In the remaining part of this section, we introduce 31 target office buildings and the simulation cases assumed in this study.

Table 1. Building properties gathered for target buildings

Category	Information
Shape and configuration	Area of each floor
	Shape of building
	Number of stories
	Zoning of floor plan
	Ratio of window to wall ratio
HVAC system	Kinds of heat source machines
	Energy source
Energy-conservation measures	energy-conservation measures adopted in buildings
Usage & operation	Principal usage
	Usage of all floor
	Operation schedule of HVAC system
Energy consumption	Electricity and city gas consumption (monthly from Apr. 2007 to Mar. 2008)

Target office buildings

The total floor area of all the buildings is 242,915m². 19 buildings are smaller than 5,000 m² while the buildings occupy 11.9% of the total floor area. Most of the buildings equip distributed HVAC system (not central system) with electricity driven heat pumps without any energy-conservation measures.

There are five buildings larger than 15,000 m². They occupy 57% of the total floor area. Four buildings equip a central HVAC system comprising of absorption chillers/heaters or compression chillers with city gas boilers. A variety of energy-conservation measures were adopted in these buildings.

The remaining seven buildings are with a total floor area between 5,000m² and 15,000m². Both central and distributed HVAC systems are used.

Table 2 outlines the floor area, share of HVAC systems and adoption ratio of five energy-conservation measures considered in this study. Table 3 show the definition of HVAC system listed in Table 2 and COP (Coefficient of Performance) of heat source machines.

Table 2. Characteristics of the target buildings

Size range	Total floor area	Number of buildings	Share of HVAC system			
			Absorption	Turbo/Boiler	AHP	Distributed
< 5000m²	28,983	19	4.4	0.0	8.7	86.9
< 15000m²	74,561	7	68.3	0.0	0.0	31.7
≥15000m²	139,371	5	57.1	14.8	0.0	28.1
Total	242,915	31	54.3	8.5	1.0	36.2

Size range	Total floor area	Adoption ratio of energy-conservation measures [%]				
		THE*	Hf lumps	VAV	VWV	NV*
< 5000m²	28,983	32.9	22.8	0.0	0.0	0.7
< 15000m²	74,561	38.2	53.4	32.2	28.5	63.9
≥15000m²	139,371	86.3	77.6	49.5	58.2	34.7
Total	242,915	65.1	63.6	38.3	42.1	39.6

* THE: Total heat exchanger; NV: Natural ventilation

Table 3. Explanation of heat HVAC system

System alternative	Heat source			
	Cooling	Cooling COP	Heating	Heating COP
Absorption	Direct gas-fired absorption chillier	1	Same as cooling	0.83
Turbo/boiler	Water-source turbo refrigerator	4.5	Boiler	0.83
AHP	Air-source heat pump driven by electricity	2.89	Same as cooling	3.12
Distributed	Distributed air-conditioning system	2.6	Same as cooling	3.2

Table 4. Simulation cases

Case	Shape & configuration	Heat source	Energy-conservation measures	Usage
Case 1	Individual	Individual	Individual	Individual
Case 2	Average	Typical	Typical	Typical
Case 3	Average	Average	Typical	Typical
Case 4	Individual	Average	Individual	Individual
Case 5	Individual	Average*	Individual	Individual
Case 6	Individual	Individual	Typical	Individual
Case 7	Individual	Individual	Individual	Typical

Simulation cases

In order to evaluate how modelling methodology influences the accuracy of simulation model, we designed seven simulation cases as explained below and Table 4:

1) Case 1

In Case 1, all the gathered information for each building is applied to predict the energy consumption. The result is supposed to be the most accurate simulation result in this study.

2) Case 2 and Case 3

Case 2 assumes the simplest modelling methodology in which only one office building model is developed and the result is applied to all the buildings. We do not classify the buildings to improve the simulation accuracy. Table 5 shows the properties of the building model. The total floor area and area of each floor is given by averaging them with the weight of the total floor area. All floors are supposed to be used for office usage. A HVAC system was assumed that consisting of absorption chillers/heaters, as the system has the largest share in the target buildings in terms of total floor area as listed in Table 3. We also assumed that total heat exchangers and high frequency fluorescent lamps (Hf lamps, which have a 23% higher luminous efficacy compared to normal fluorescent lamps) are adopted in the model as these energy-conservation measures are adopted in more than a half of the total floor area as shown in Table 3.

While only typical HVAC system is considered in Case 2, the variety in HVAC system is taken into account in Case 3. We calculate the energy consumption while assuming the four HVAC systems with the building model designed for Case 2. We then average the result with a weight of the share of these systems.

3) Case 4 and Case 5

In Case 4 and Case 5, we calculate the energy consumption of all the target buildings individually by applying all the gathered information except those of the configuration of HVAC system.

As shown in Table 3, configuration of HVAC system varies according to the size of buildings. In Case 4 and Case 5, we assume that building stock is classified according to the configuration of HVAC system. The energy consumption of each building is calculated assuming the four HVAC systems and then the result is averaged with the weight of the share of HVAC systems.

In Case 4, the share of HVAC system configuration is given by that in the total floor area. In Case 5, we assumed to classify the building stock by the size range (less than 5,000m², 5,000m² to 15,000m² and larger than 15,000m²) and the configuration of HVAC system. The share of HVAC system in each size range is utilized when the energy consumption is quantified.

By comparing the results of Case 4 and Case 5, how classifying the building stock according to building size and configuration of HVAC system contributes to improving the simulation accuracy.

Table 5. Building model used in Case 2

Total floor area	20,947 m²
Area of each story	1,396 m²
Number of stories	15 (14 stories above the ground and 1 underground)
Window to Wall ratio	20%
HVAC system	Absorption chillers/heaters
Usage	Office only
Energy-conservation measures	Total heat exchanger Hf fluorescent lamps

4) Case 6

In Case 6, the energy consumption of each building is calculated individually while assuming all buildings equip the same combination of energy-conservation measures as assumed in Case 2. By comparing Case 1 and Case 6, how classification of the building stock according to the energy-conservation measures contributes to the simulation accuracy.

5) Case 7

In Case 7, all the buildings are assumed to be used only for office usage. By comparing Case 1 and Case 7, the influence of building usage can be evaluated.

Simulation conditions

In addition to the monthly and annual energy consumption, potential carbon dioxide emission reduction is estimated for Case 1 and Case 5 to Case 7, which are gained by assuming total heat exchanger, Hf fluorescent lamps, VAV and VWV control and natural ventilation are fully disseminated in the target buildings. We use carbon dioxide emission factor of 0.338 kg-CO_2/kWh for electricity and 0.0506kg-CO_2/MJ in this study.

RESULT

Case 1: full implementation of the gathered data

Figure 4 and Figure 5 show measured electricity and city gas consumption and those estimated in Case 1. The figures show a good agreement on both electricity and city gas. Comparing annual amounts, the difference is -2.0% in electricity consumption and 4.4% in city gas. However, the simulation result of electricity is smaller than the measured data during the summer season from June to September. For the gas consumption, the simulation result is smaller in summer and larger in winter. These discrepancies in both electricity and city gas can mainly be attributed to variation in the input parameters of the model with those of actual buildings, especially where default values were used. For example, common operation conditions were assumed if floors are used for same usage. Only one kind of heat source machine was assumed for heating and cooling individually, while there are a number of buildings which heat source consists of a few kinds. There might also be limitations in accounting for physical and operational conditions of, for example, uncontrolled heat losses or gains from heating and cooling distribution systems (duct and pipes), and energy increases due to inappropriate design, operation of HVAC systems as well as deterioration of energy performance of appliances and equipment.

Case 2 and Case 3: modelling by a single prototypical building model

Figure 5 and Figure 6 compare the predicted monthly electricity and city gas consumption in Case 2 and Case 3, in addition to measured data and those of Case 1. In Case 2, there is a large gap between estimated and measured data in both electricity and city gas. The result shows that if the energy use of a certain amount of building stock is modelled by using only one prototypical building model, the simulation result potentially contains a large range of uncertainty. However, as shown in the result of Case 3, the accuracy can be improved by taking the distribution of HVAC system configuration into account in the model.

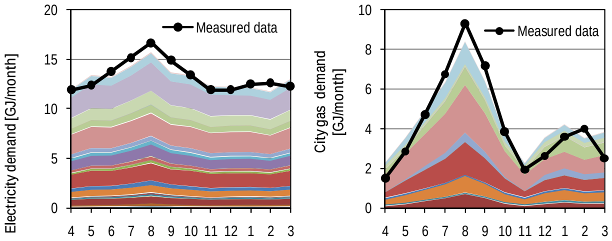

Figure 4. Total monthly electricity consumption (left) and gas consumption (right)

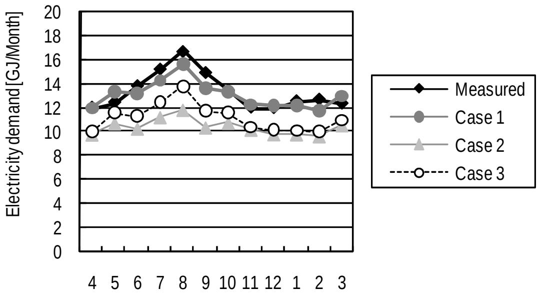

Figure 5. Monthly electricity demand of Case 1 to Case 3

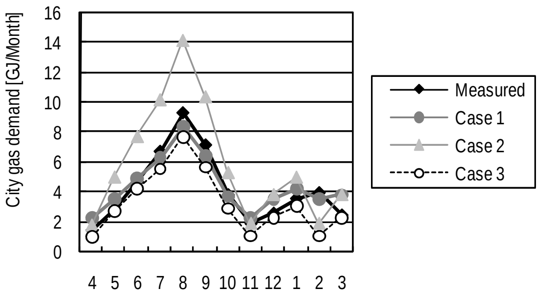

Figure 6. Monthly city gas demand of Case 1 to Case 3

Case 4 and Case 5: consideration of the distribution of HVAC systems

Here, we compared the result of Case 4 and Case 5 with those of Case 1. We calculated the difference from the result of Case 1 for buildings in three size rages. Figure 7 and Figure 8 show the result.

A large error was observed in Case 4 in the result of city gas of buildings in the size range smaller than 5,000m² as shown in Figure 8. This error can be improved by taking distribution of HVAC system into account in the model as in Case 5.

Case 5 to Case 7

Table 6 shows the predicted annual electricity, city gas consumption and potential carbon dioxide emission reduction due to dissemination of heat exchanger, Hf lamps, VAV, VWV and natural ventilation in Case 1 and Case 5 to Case 7. Table 6 also shows discrepancy in these indicators calculated for Case 5 to Case 7 based on the result of Case 1.

Table 6. Simulation result of electricity, city gas, CO_2 and discrepancy from those of Case 1

Size range	Indicator	Unit	Annual quantity				Discrepancy from Case 1		
			Case 1	Case 5	Case 6	Case 7	Case 5	Case 6	Case 7
< 5000m²	Electricity	MJ/m²	509.5	513.6	474.9	691.7	-0.8%	6.8%	-35.8%
	City gas	MJ/m²	50.1	55.9	49.7	23.5	-11.6%	0.8%	53.1%
	CO_2 reduction	kg-CO_2/m²	6.8	6.6	3.5	10.1	-2.1%	-47.9%	48.9%
< 15000m²	Electricity	MJ/m²	635.4	635.0	613.3	580.2	0.1%	3.5%	8.7%
	City gas	MJ/m²	256.4	295.8	240.9	260.0	-15.3%	6.1%	-1.4%
	CO_2 reduction	kg-CO_2/m²	11.4	11.3	8.6	12.6	-1.0%	-24.9%	10.9%
≥ 15000m²	Electricity	MJ/m²	680.1	681.8	622.5	641.0	-0.2%	8.5%	5.7%
	City gas	MJ/m²	233.3	224.6	230.4	196.3	3.7%	1.2%	15.8%
	CO_2 reduction	kg-CO_2/m²	11.5	11.8	6.0	12.0	2.0%	-47.8%	3.7%
Total	Electricity	MJ/m²	646.0	647.4	602.1	628.4	+0.2%	-6.8%	-2.7%
	City gas	MJ/m²	218.5	226.3	212.1	195.2	+3.6%	-2.9%	-10.7%
	CO_2 reduction	kg-CO_2/m²	10.9	11.0	6.5	11.9	+0.7%	-40.5%	+9.4%

Case 5 showed the smallest discrepancy from Case 1 in these indicators. The error in the potential reduction in carbon dioxide is less than 3% in any size range.

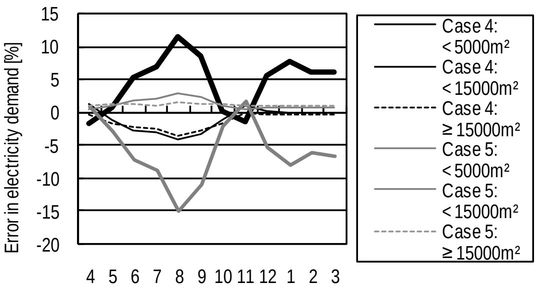

Figure 7. Difference between estimated electricity demands of Case 4 and Case 5 with Case 1

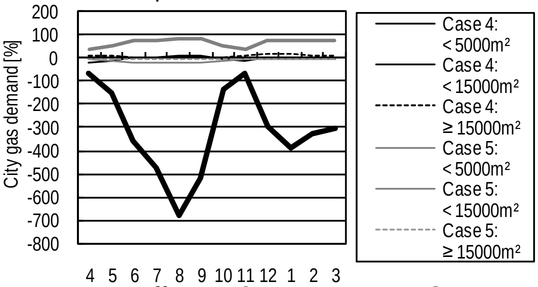

Figure 8. Difference between estimated city gas demands of Case 4 and Case 5 with Case 1

Case 5 to Case 7

Table 6 shows the predicted annual electricity, city gas consumption and potential carbon dioxide emission reduction due to dissemination of heat exchanger, Hf lamps, VAV, VWV and natural ventilation in Case 1 and Case 5 to Case 7. Table 6 also shows discrepancy in these indicators calculated for Case 5 to Case 7 based on the result of Case 1.

Case 5 showed the smallest discrepancy from Case 1 in these indicators. The error in the potential reduction in carbon dioxide is less than 3% in any size range.

On the other hand, the result of Case 6 showed a significant error in the potential reduction in carbon dioxide emission. This error can be attributed to the assumption of energy-conservation measures. We assumed that Hf fluorescent lamps were adopted in Case 6 because Hf lamps are currently adopted in more than half of total floor area as shown in Table 2. In order to avoid over- and under-estimation, the current distribution of energy-conservation measures must be appropriately taken into account in the model when the model is designed to estimate potential contributions of energy-conservation measures.

In Case 7, the error in the potential carbon dioxide emission is approximately 10% in total and two larger size ranges. However, it is reached to 50% in the smallest size range. In Japanese commercial sector, buildings in the range occupy approximately half of the total floor area. Thus, simplification of floor usage potentially leads to a large overestimation in the potential contribution of energy-conservation measures.

Summary and implications

First, modelling the energy use of a certain amount of building stock by using only one prototypical building model would involve significant uncertainty in the simulation result as shown in Case 2. The result from Case 3 to Case 7 demonstrated that classification of building stock, which homogenizes a building stock group in which energy use is modelled by one prototypical model, contributes to improving the accuracy of simulation result. We especially focus on consideration of the configuration of HVAC system, energy-conservation measures, and space usages. The result in Case 5 to Case 7 showed the extent to which the simulation result deteriorates by simplifying these parameters.

The method assuming the configuration of HVAC system has a significant influence on the simulation result of electricity and city gas, or the share of secondary energy consumption. The error due to the configuration of HVAC systems can be avoided by dividing building stock into several categories and apply the share of HVAC system in each building stock category.

The assumption of the energy-conservation measures is crucial when the developed model is applied to evaluate the potential contribution of energy-conservation measures. In order to avoid over- and under estimation of the contribution, the current distribution of energy-conservation measures must be appropriately addressed in the model.

The method assuming the floor usage is also important to model the energy demand of commercial sector buildings because commercial sector buildings often consist of a variety of usages in Japan, especially when the approach is applied to stock groups of small buildings. Ignoring the mix of usage potentially results in uncertainty in the simulation result.

In our model of the commercial sector of Osaka city, only one pattern of space usages (usages of each floor of prototypical building models) is designed for each size range of each principal usage building stock category. Although the pattern is designed based on the share of total floor area for space usages given by a large number of sample buildings, the accuracy of the model can be improved by taking the variation in the space usage into account. On the other hand, the error due to configuration of HVAC system and energy-conservation measures would be limited as we divided the building stock according to eight kinds of HVAC systems and five combinations of energy-conservation measures in addition to adoption of Hf fluorescent lamps and insulation of building envelops.

CONCLUSION

This paper discussed the relationship between the accuracy of simulation models and the methodology adopted for modelling the energy consumption of a certain amount of building stock. In order to improve the accuracy, the building stock must be divided into a number of groups taking into account the variation in the building size, configuration of HVAC system, combination of energy-conservation measures and space usage. The configuration of HVAC system has a significant influence on the amount of electricity and city gas consumptions. The distribution of energy-conservation measures must be addressed in the model in order to avoid over- and under-estimation to predict a potential contribution of energy-conservation measures and technologies. Space usage must be addressed in the model as well if the building stock consists of a variety of usages.

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