# URBAN SCALE MODELLING OF ENERGY DEMAND OF RETAIL FACILITIES

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## ABSTRACT

This paper reports the development process of an urban-scale energy demand model of retail facilities located in the Keihanshin metropolitan area, Japan. First, we used statistical analysis of actual energy consumption data and interviews with facility managers and professionals of industry organizations to define building stock categories. We next developed archetypes to represent each stock category, and we estimated energy use intensity (EUI) of each stock category by using the archetypes as input in performing an entire building energy usage simulation. Finally, we calculated the total energy consumption of retail facilities in the Keihanshin area by using the total sales floor area. The developed model can be applied to evaluate potential change in energy demand due to changes in technologies, climate and builing stock.

## INTRODUCTION

Of the many urban-scale models developed in recent years for estimating the energy usage of building stocks, the most commonly used methodology is the archetype engineering model, as discussed by 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, and an archetype model, representative of a particular building category, is then developed. The unit energy consumption for each category is next quantified by conducting building performance simulations by using the archetypes as input. Finally, the total energy consumption is quantified by multiplying the unit energy consumption by the number of units in each stock category.

The classification process is important because the characteristics of energy usage of commercial buildings are significantly diverse. Figure 1 shows the cumulative frequency of total floor area and energy use intensity (EUI) of Japanese retail facilities (Yamaguchi et al. 2012). Because a logarithmic scale is used for the axes, the EUI and total floor area are widely distributed. This figure implies that the classification of commercial buildings by retail category considerably reduces the variety in energy usage by homogenising each category.

The archetype design and simulation processes are also important because they allow the developed simulation model to reflect the structure by determining energy usage in each stock category. For example, although home centres are in operation daily, the quality of indoor environment is not high; the EUI per total floor area for this category ranges from 1,000 to 3,000 MJ/m²·yr. On the contrary, because food supermarkets are equipped with high-

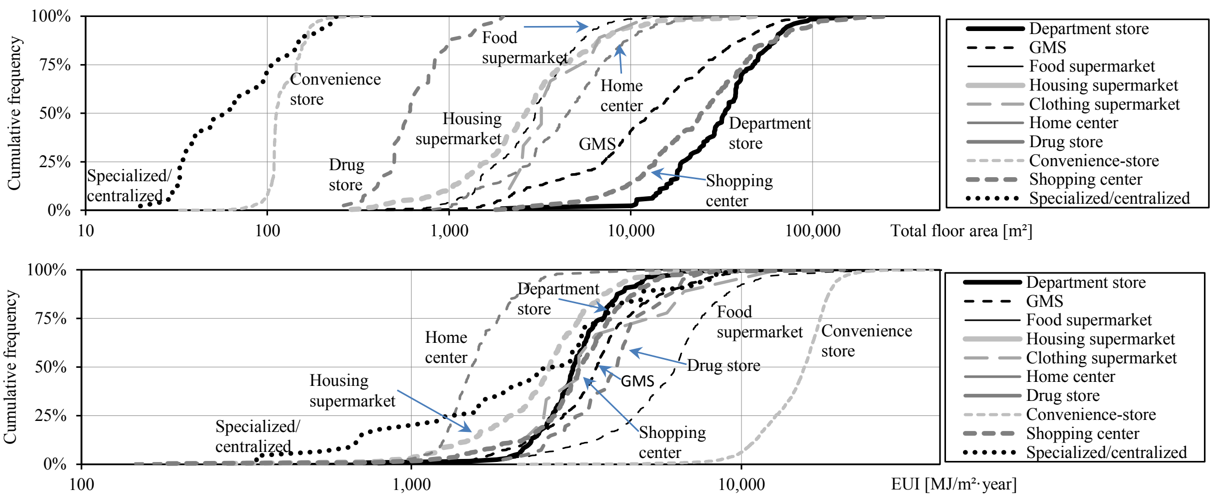


*Figure 1 Distribution of total floor area and energy use intensity of the various types of commercial buildings in Japan*

capacity refrigeration systems, the EUI for this type ranges from 5,000 to 20,000 MJ/m²·yr.

The purpose of this paper is to use the aforementioned procedure to develop an urban scale energy demand model for the retail sector of the Keihanshin metropolitan area in Japan. The Keihanshin metropolitan area is a region encompassing the cities of Osaka in Osaka prefecture, Kobe in Hyogo Prefecture, and Kyoto in Kyoto prefecture, located in the middle of the Japanese Main Island. The entire area is 27 thousand km$^2$ and has a population of approximately 21 million, equivalent to 16% of Japan's population. It is Japan's second most populated urban region after the Greater Tokyo Area. According to national statistics, the total sales area of the retail facilities in the area was 22 million m² in 2007. To consider the variety of retail building types, the classification process must be carefully followed, and factors influencing energy consumption, must be fully incorporated during the archetype design process. Such factors include physical properties of the facilities, operation schedule, capacity and operation of lighting, appliances, air-conditioning systems and other device such as refrigeration display cabinets for food sales. The remaining part of this paper reports each process of the model development procedure. Finally, we discuss the strengths and weaknesses of the model development procedure, and we outline our future works.

## CLASSIFICATION OF RETAIL FACILITIES

Yamaguchi et al. (2012) gathered the annual energy consumption data of 5,869 retail facilities and classified the samples into 11 retail categories, as shown in Figure 1. The mean value of EUI was statistically compared among the retail categories, and most showed a statistically significant difference. This result implies that the retail category characterizes both influencing factors of energy consumption and EUI.

Yamaguchi et al. (2012) also showed that EUI of general merchandise supermarkets (GMS), food supermarkets, drug stores, department stores and shopping centres varies significantly with building size. This result implies that these facilities should be further classified by size. To confirm this hypothesis, we divided the samples by sales area for the retail categories and compared mean EUI differences. The classification by facility size is also beneficial in considering the differences in the configuration of building facilities and, more specifically, the adoption ratio of energy conservation measures and the share of heat source systems.

To develop each stock category, we conducted a literature survey and interviewed facility development managers and industry professionals, in addition to a refrigeration equipment manufacturer, to investigate the characteristics and trends of retail facilities. On the basis of these surveys, the following main points were identified:

- The planning process of a new facility includes selection of the site considering its trade area, identifying the facility's concept and selection of retail goods to determine retail category, and designing the building and facilities.
- Companies that own several retail facilities have design prototypes of retail facilities that are repeatedly referred in the design process. In addition, such design prototypes are often shared by industry professionals.

These results imply that in addition to the retail category, sales floor area of facilities influences energy consumption.

After determining several retail categories by sales floor area, we discovered that some categories shared influencing factors of energy consumption such as capacity and operation of appliances and equipment. Food supermarkets larger than 3,000 m$^2$, known as mega food supermarkets, tend to have larger floor areas for clothing and housing sales. Such supermarkets share characteristics with small GMS and shopping centres, known as neighbourhood shopping centres, that sell a variety of retail goods including food. Thus, we created a category of small general merchandise (GM) facility that combines these characteristics. Similarly, the characteristics of

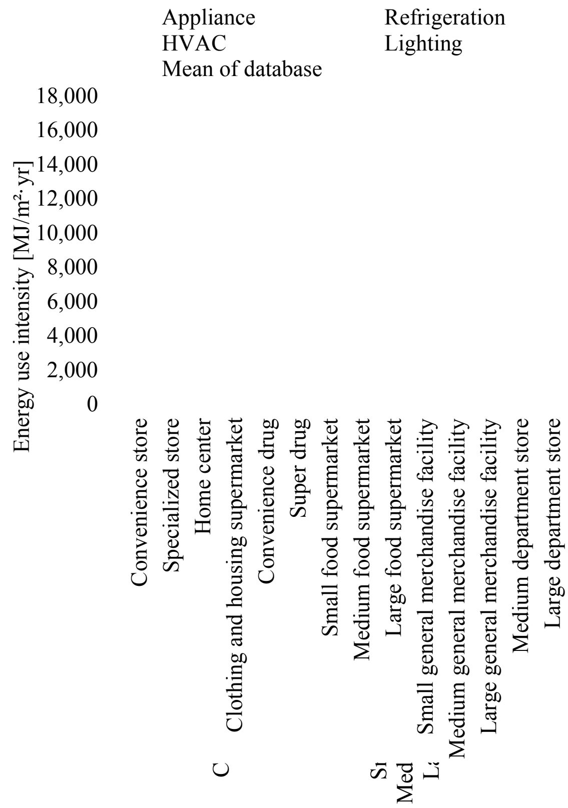


*Figure 2 Average energy use intensity for each stock category*

*Table 1 Definitions of building stock categories*

| **Building stock category** | **Sales area[m$^2$]** | **Segment-category** | **Retail category** | **Survey method for segmentation** |
|---|---|---|---|---|
| Convenience store | ≥30<br><250 | | Convenience store | |
| Specialized store | <250 | | Specialized store | |
| Home centre | ≥250 | | Home centre | |
| Clothing and housing supermarket | ≥250 | | Clothing supermarket | |
| | | | Housing supermarket | |
| Convenience drug | <1,000 | Convenience drug | Drug store | Survey for professionals<br>·Japan Association of Chain Drug Stores<br>Literature survey<br>·Commercial Facility: Creation and Design (JTOCS, 2008) |
| Super drug | ≥1,000 | Super drug | | |
| Small food supermarket | <1,000 | Small food supermarket | Food supermarket | Survey for professionals<br>·Japan Supermarkets Association<br>·New Supermarket Association of Japan<br>·Study Group of Eco-friendly Store<br>·Chain store A of food supermarket and GMS<br>·Manufacturer B of refrigeration equipments<br>·Japan Council of Shopping Centers<br>Literature survey<br>·Commercial Facility: Creation and Design (JTOCS, 2008) |
| Medium food supermarket | <2,000 | Medium food supermarket | | |
| Large food supermarket | <3,000 | Large food supermarket | | |
| Small general merchandise facility | <10,000 | Mega food supermarket | | |
| | | Small GMS | General merchandise supermarket (GMS) | |
| | | Neighborhood SC | Shopping centre (SC) | |
| Medium general merchandise facility | <30,000 | Medium GMS | GMS | |
| | | Community SC | SC | |
| Large general merchandise facility | ≥30,000 | Large GMS | GMS | |
| | | Regional SC | SC | |
| Medium department store | <30,000 | Medium department store | Department store | Literature survey<br>·Commercial Facility: Creation and Design (JTOCS, 2008)<br>·Trend of Commercial Facilities 2009 (Yano Research Institute, 2008) |
| Large department store | ≥30,000 | Large department store | | |

We did not combine department stores with food supermarkets, GMS and shopping centres because department stores do not offer the self-service system, which is adopted in these three retail categories. In addition, the environmental quality of department stores is generally higher, which could result in higher energy consumption for lighting and air conditioning.

In addition, because the characteristics of clothing and housing supermarkets were similar, we combined the two to create the category of clothing and housing supermarket.

On the basis of this analysis, we defined 14 building stock categories, as listed in Table 1, and validated each by statistically comparing the mean EUI. Figure 2 shows the mean with a 95% confidence interval of each stock category, which depended on the number of samples. The super drug category showed a relatively large interval because the number of samples was only five. Thus, specialized store and large GM facility showed a large interval. Except for these combinations, the categories showed statistically significant differences in mean EUI.

These results imply that classification by stock categories contributes to the homogenisation of retail facilities within each stock category.

## DEVELOPMENT OF BUILDING ARCHETYPES

In the previous section, we developed 14 stock categories for retail facilities. For each stock category, we designed a building archetype according to a set of input data for building performance simulation to estimate the EUI. Thus, the archetypes defined geometry and physical properties of the buildings; capacity and operation of lighting and heating, ventilation and air conditioning (HVAC) systems; and refrigeration systems and other appliances. Moreover, the archetypes were carefully designed to reflect the characteristics of energy usage in each stock category.

**Building geometry and business hours**

The statistical data shown in Figure 1 was collected during Japanese DECC project (Japan Sustainable Building Consortium, 2012). In addition, data of sales area, total floor area, number of stories and business hours were collected and used to design the geometry and business hours of archetypes (Table 2). The total floor area was divided into two categories of sales area and non-sales area, the latter of which was used for management offices, work spaces and storerooms.

**Specification and operation of lighting and appliances**

The intensity of lighting and appliances was designed on the basis of a literature survey that considered the differences among stock categories.

The intensity of lighting for clothing and housing sales was designed to be higher than that of food sales. In particular, the intensity of lighting in medium and large department stores was designed to be higher than that in other categories because such stores do not offer a self-service system, and indoor environmental quality is relatively high. The intensity of appliances of sales area was defined as 13.5 W/m$^2$ for convenience store, 10 W/m$^2$ for medium and large department stores and 2 W/m$^2$ for other categories to deliver services and display sales items.

For convenience and super drug, the intensity of lighting was defined as 40 W/m$^2$ to consider cosmetics and beauty products.

**Configuration of HVAC system**

Yamaguchi et al. (2010) developed a database on HVAC systems in which the shares of six types were distinguished according to retail facility size. Table 3 shows the heat source and coefficient of performance (COP) of these HVAC systems, and Table 4 shows HVAC system shares and sizes of facilities. To take into account the share of each HVAC system configuration, the EUI was calculated while assuming all configurations respectively, and the result was weighted averaged by using the share of the system configurations.

*Table 2 Definitions of archetypes of building stock categories*

| Building stock category | Sales area [m$^2$] | Total floor area [m$^2$] | Number of stories | Store hours | Capacity per sales area [W/m$^2$] | |
|---|---|---|---|---|---|---|
| | | | | | Lighting | Refrigeration system |
| Convenience store | 110 | 183 | 1 | Around the clock | 20 | 136 |
| Specialized store | 66 | 110 | 1 | 11:00-20:00 | 30 | |
| Home centre | 4,700 | 7,231 | 1 | 10:00-21:00 | 20 | |
| Clothing and housing supermarket | 3,900 | 6,000 | 2 | 10:00-21:00 | 40 | |
| Convenience drug | 580 | 892 | 1 | 10:00-21:00 | 40 | 2 |
| Super drug | 1,600 | 2,462 | 1 | 10:00-21:00 | 40 | 4 |
| Small food supermarket | 820 | 1,262 | 1 | 8:00-23:00 | 20 | 120 |
| Medium food supermarket | 1,500 | 2,308 | 1 | 9:00-22:00 | 20 | 59 |
| Large food supermarket | 2,500 | 3,846 | 1 | 9:00-22:00 | 20 | 47 |
| Small general merchandise facility | 6,200 | 9,538 | 3 | 10:00-21:00 | 1st floor 20<br>The others 40 | 1st floor 24 |
| Medium general merchandise facility | 15,000 | 27,273 | 3 | 10:00-21:00 | 1st floor 20<br>The others 40 | 1st floor 24 |
| Large general merchandise facility | 51,000 | 92,727 | 4 | 10:00-22:00 | 1st floor 20<br>The others 40 | 1st floor 24 |
| Medium department store | 18,000 | 32,727 | 8 | 11:00-20:00 | 80 | |
| Large department store | 42,000 | 76,364 | 12 | 11:00-21:00 | 80 | |

*Table 3 Definitions of heat sources and coefficient of performance (COP) of HVAC system types*

| System alternative | Heat source | | | | CGS |
|---|---|---|---|---|---|
| | Cooling | Cooling COP | Heating | Heating COP | |
| CGS | Direct gas-fired absorption chiller | 1.00 | Same as cooling | 0.83 | Use |
| Ab | Direct gas-fired absorption chiller | 1.00 | Same as cooling | 0.83 | |
| Ab&Bo | Double effect absorption chiller driven by steam | 1.00 | Boiler | 0.83 | |
| Cc&Bo | Compression chiller | 4.50 | Boiler | 0.83 | |
| DisAC | Distributed air-conditioning system driven by electricity | 2.60 | Same as cooling | 3.20 | |
| GHP | Gas engine heat pump driven by city gas | 0.95 | Same as cooling | 1.19 | |

*Table 4 Shares of HVAC system types and facility sizes*

| System alternative | Building stock category | | | |
|---|---|---|---|---|
| | **Convenience store<br>Specialized store<br>Convenience drug<br>Small food supermarket** | **Home centre<br>Clothing and housing supermarket<br>Super drug<br>Medium food supermarket<br>Large food supermarket** | **Small general merchandise facility<br>Medium general merchandise facility<br>Medium department store** | **Large general merchandise facility<br>Large department store** |
| CGS | 0% | 0% | 1% | 4% |
| Ab | 9% | 25% | 54% | 74% |
| Ab&Bo | 0% | 0% | 1% | 1% |
| Cc&Bo | 2% | 2% | 4% | 9% |
| DisAC | 76% | 60% | 31% | 8% |
| GHP | 13% | 13% | 9% | 4% |

### Refrigeration systems

Convenience stores; convenience and super drugs; small, medium and large food supermarkets; and small, medium and large GM facilities are equipped with refrigeration cabinets to display foods. The capacities of these refrigeration systems were determined through interviews with facility development managers and professionals of refrigeration system manufacturing companies. For small, medium and large food supermarkets, the most common configuration and capacity was determined on the basis of available statistics.

### Floor usage

We determined the typical floor usage for the stock categories that included more than one story such as GM facilities and department stores. For small, medium and large GM facilities, the ground floor was defined as a food sales floor equipped with refrigeration cabinets; for medium and large department stores, the basement floor was defined as a food sales floor. For both, the other floors were defined as clothing and housing sales floors.

### Other elements

For other elements of facilities, common conditions were applied to all stock categories.

## ESTIMATION OF ENERGY USE INTENSITY OF STOCK CATEGORIES

### Simulation model

The developed archetypes were used as input datasets for an entire building energy demand model to estimate EUI for each stock category.

Figure 3 shows the model used to estimate energy consumption, which calculates end-use energy demand and corresponding energy consumption for heating, cooling, ventilation, lighting, refrigeration and other (Yamaguchi et al. 2010). In this model, we did not include end use for water heating and cooking. The minimum unit for simulation was one building floor. To estimate heating and cooling demands of a

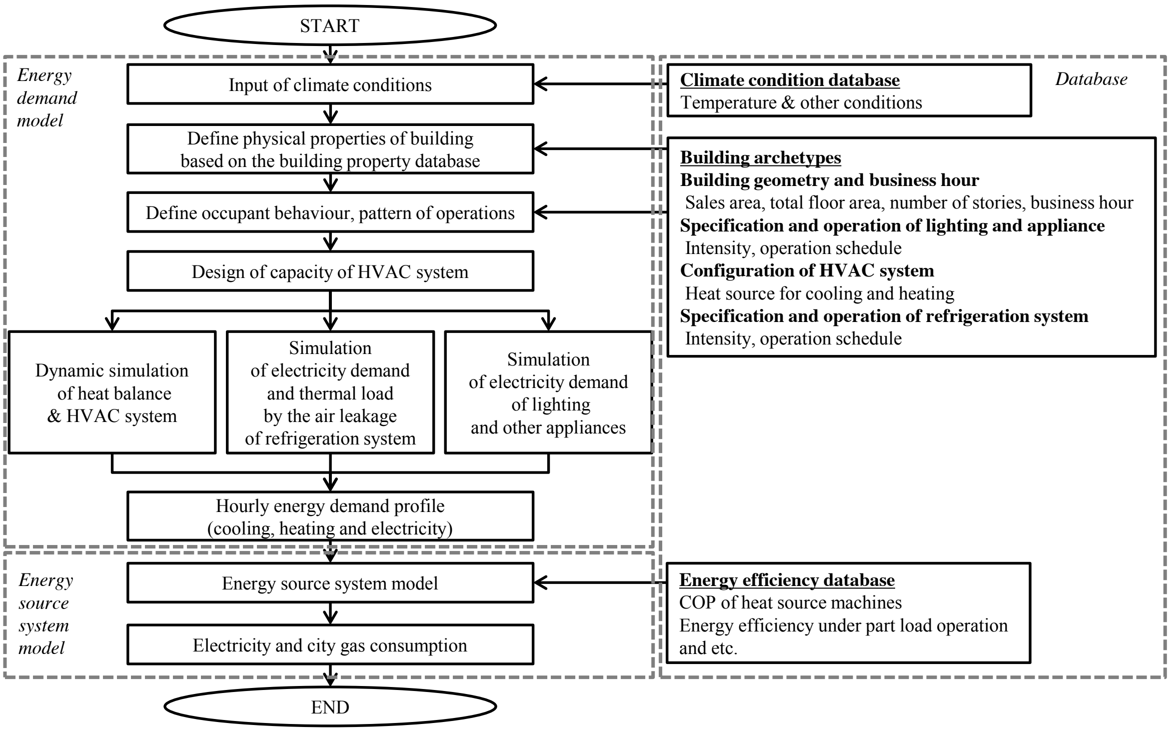


*Figure 3 Simulation procedure and databases for models used in this study*

floor, thermodynamic and HVAC system simulations were performed on an hourly basis while considering the following parameters: size, form and other properties that determine thermodynamic characteristics of the floor; usage of the floor, which determines internal heat gain and operation conditions of the HVAC system; and the adopted energy-conservation measures and configuration of HVAC systems, which determine the energy efficiency of these systems. For the simulation of electricity usage, a common electricity demand profile for lighting and other equipment was assigned to each floor.

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).

Because of the bottom-up manner in estimating EUI of each archetype, the energy demand profile and total energy consumption calculated for each archetype taking into account the influence of meteorological conditions; building geometry and property; configuration and operation of HVAC systems, lighting, appliances and other building equipment.

**Estimation result of energy use intensity**

Figure 4 shows the primary energy consumption per total floor area estimated for each building stock category. The figure also shows the mean EUI with a 95% confident interval, which was also shown in Figure 2.

The simulation result was generally in good agreement with the actual EUI, with the exception of convenience drug. This result implies that the archetype designs successfully reflected differences among stock categories. Figure 4 also shows the composition of energy consumption by end use. In convenience store and small, medium and large food supermarkets, the share of refrigeration energy accounted for more than 50%, and the total EUI was significantly higher than that for other stock categories.

## AGGREGATION OF ENERGY CONSUMPTION

In the final step, the total energy consumption of retail facilities located in the Keihanshin metropolitan area, Japan, was quantified by aggregating the estimated total energy consumption of all stock categories. This process considered total sales floor area and the EUI quantified in the previous step. It should be noted that while the total floor area was used in Figure 4 for comparison with the actual EUI shown in Figure 2, we used sales area as the unit because it was the only data available for aggregation.

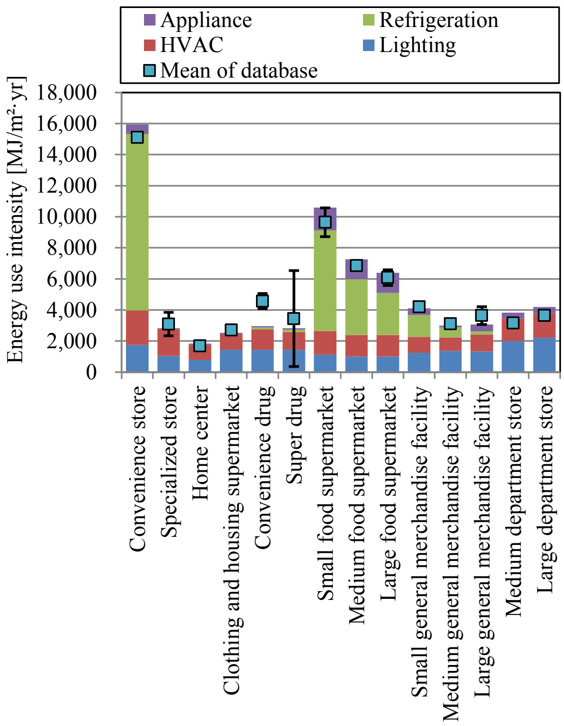


*Figure 4 Energy use intensity of archetypes*

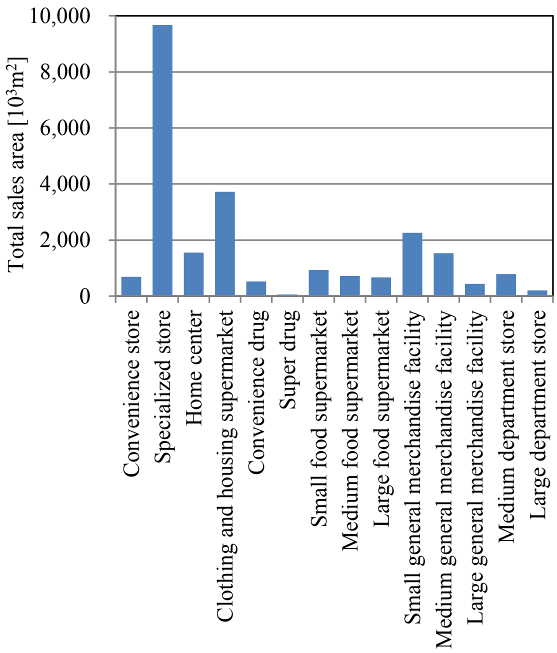


*Figure 5 Total sales floor areas for stock categories in the Keihanshin metropolitan area*

**Total sales floor area**

The Research and Statistics Department of the Ministry of Economy, Trade and Industry (METI), Japan, conducts a Census of Commerce every five years. The purpose of the census is to clarify the actual conditions of the nation's commerce and to obtain basic data for the formulation of commercial policy (METI, 2012). Survey results, which are published online, include sales floor area.

Figure 5 shows the estimated total sales floor area of each stock category in the Keihanshin metropolitan area.

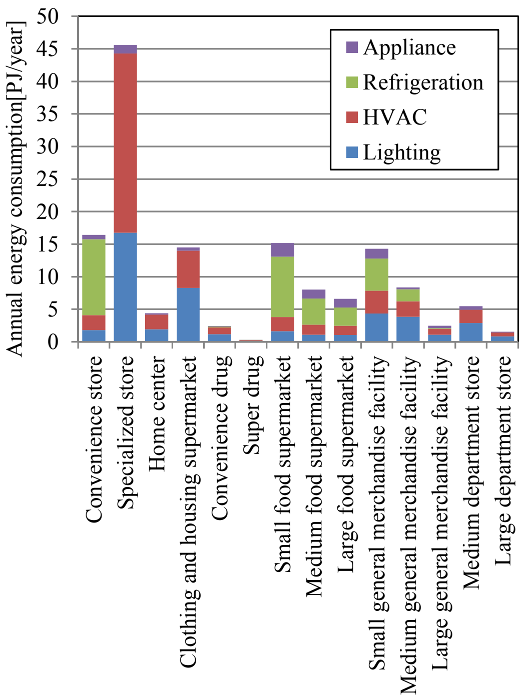


*Figure 6 Energy consumption among stock categories*

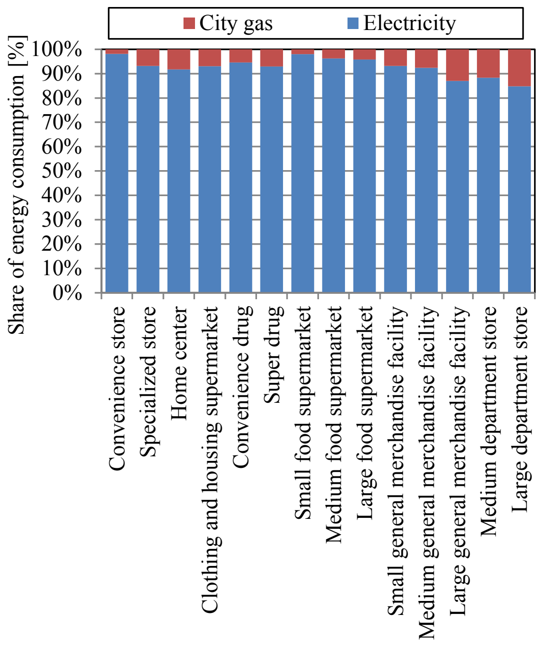


*Figure 7 Electricity and city gas consumption among stock categories*

### Energy consumption

The total energy consumption of each category was calculated by multiplying the total sales floor area with the EUI per sales area. Figure 6 shows the total energy consumption of each stock category. The total energy consumption of the stock category of specialized store is the largest, which corresponds to the largest sales area in the region shown in Figure 5. Figure 7 shows the share of electricity and city gas consumption. The rate of gas consumption differed among the stock categories from 2% to 15%. The stock categories with large floor areas tended to show relatively large shares of gas consumption. This result occurred likely because the share of Ab or Ab and Bo driven by city gas is high among HVAC system configurations in large buildings, as listed in Table 4.

Finally, we quantified the total energy consumption in the Keihanshin metropolitan area; the calculated annual primary energy consumption was 146 PJ/year. Figure 8 shows energy consumption by end use and energy source. Energy consumption for lighting and HVAC accounted for approximately 70% of the total energy consumption. Energy consumption for refrigeration was also significantly high at 24%.

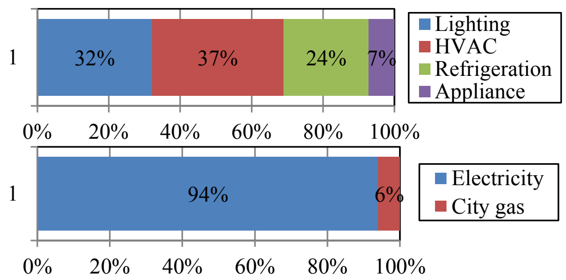


*Figure 8 Shares of total energy consumption in the Keihanshin metropolitan area*

## DISCUSSION

This case study successfully demonstrated the applicability of the archetype engineering approach to Japanese retail facility stocks with significantly diverse levels of EUI. The process used in this approach consisted of stock classification, archetype design, simulation using archetype and energy consumption aggregation. The classification of building stock allowed the model to design an archetype that represented a homogenised stock group. The archetype design considered the features of each stock category, and the simulation process used archetypes reflecting the energy consumption of the stock category. The final aggregation step reflected the distribution of building stock in each stock category. The capability of the developed model was appropriate for applications to evaluate potential contributions of specific technologies such as LED light and policy implementation.

However, it should be noted that this approach has a significant weakness. Figure 1 shows the actual distribution of EUI in retail facilities. By classifying retail facilities according to the 14 stock categories, it is possible decrease variety in EUI. However, large variability in each stock category remains, as shown in Figure 1. It is impossible to consider the variability in EUI with the archetype engineering model. Because such variability could be caused by number of factors, it is necessary to apply a probabilistic approach, which gives input parameters as statistical distributions in the simulation process using the archetypes. This point is discussed further by Yamaguchi et al. (2013).

## CONCLUSION

This paper discussed the methodology to develop an urban-scale energy demand model of a retail sector building located in the Keihanshin metropolitan area in Japan. We classified retail facilities into 14 building stock categories according to the characteristics of energy consumption. We developed archetypes for each category by considering differences in the influencing factors of energy consumption among the categories. We simulated EUI by using the archetypes as input and determined that the result is in good agreement with the actual EUI, with the exception of convenience drug. In addition, the simulation result can show the composition of energy consumption for each end use. Finally, we calculated the total energy consumption of retail facilities in area by calculating energy consumption for all clusters quantified by multiplying energy use intensity and total sales floor area; the calculated annual primary energy consumption was shown to be 146 PJ/year. The result indicated energy consumption by end use and by electricity and city gas. Therefore, this model is capable of urban-scale simulation of retail sectors while considering the wide variety of energy usage of retail facilities. The developed model can be applied to evaluate potential changes in energy demand due to technologies, climate and building stock. It is also possible to estimate peak electricity demand of retail facilities during summer season that is made by high electricity demand for cooling and refrigeration. .

## ACKNOWLEDGMENTS

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