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# Effect of facade components on energy efficiency in office buildings

Takeshi Ihara [a,b,*], Arild Gustavsen [a], Bjørn Petter Jelle [c,d]

[a] Norwegian University of Science and Technology (NTNU), Department of Architectural Design, History and Technology, NO-7491 Trondheim, Norway
[b] Takenaka Research and Development Institute, Chiba 270-1395, Japan
[c] Norwegian University of Science and Technology (NTNU), Department of Civil and Transport Engineering, NO-7491 Trondheim, Norway
[d] SINTEF Building and Infrastructure, Department of Materials and Structures, NO-7465 Trondheim, Norway

## HIGHLIGHTS

- Investigation of facade properties for energy efficiency of Tokyo office buildings.
- Higher reflectance for opaque parts may slightly reduce energy demand.
- Lower window *U*-value and solar heat gain coefficient are potential solutions.
- Decreased heating due to insulation did not always compensate increased cooling.
- Fundamental data for adjustment of facade properties of buildings are provided.

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## ABSTRACT

Properties of facade materials should be considered to determine which of them strongly affect building energy performance, regardless of the building shapes, scales, ideal locations, and building types, and thus may be able to promote energy efficiency in buildings. In this study, the effects of four fundamental facade properties related to the energy efficiency of office buildings in Tokyo, Japan, were investigated with the purpose of reducing the heating and cooling energy demands. Some fundamental design factors such as volume and shape were also considered. It was found that the reduction in both the solar heat gain coefficient and window *U*-value and increase in the solar reflectance of the opaque parts are promising measures for reducing the energy demand. Conversely, the reduction in the *U*-value of the opaque parts decreased the heating energy demand, and this was accompanied by an increase in the cooling energy demand in some cases because the total energy demands were predominantly for cooling. The above-mentioned promising measures for reducing building energy demands are thus recommended for use, and an appropriate *U*-value should be applied to the opaque parts based on careful considerations. This study provides some fundamental ideas to adjust the facade properties of buildings.

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## 1. Introduction

The use of an energy-efficient facade is indispensable for reducing carbon emissions during the operational phase of a building. Facade factors related to energy performance are thermal quantities (e.g., *U*-value) and solar heat gain quantities (e.g., solar heat gain coefficient (SHGC)). Indeed, several new facade materials have been developed that are aimed at reducing the energy demands of buildings [1–5]. The development of facade materials should be promoted to realize a more energy-efficient facade, which could potentially be a universal solution regardless of the two facts that (1) locations, weather, and user behavior strongly affect energy performance and its distribution and (2) facade properties (e.g., reflectance, *U*-value of opaque and window parts, and SHGC) and design factors (e.g., building shape, volume, and window configuration) dependently affect the building energy properties. From a material point of view, there is no universal solution recommended for the former fact. Regarding the latter fact, there may be a potential demand for considering facade properties that affect energy performance in a phase such as the material development phase. It is therefore important to estimate which facade properties could have a strong effect in reducing energy demands, regardless of the design factors. Thus far, previous studies have focused on either a specified building shape or a specified component as described below.

* Corresponding author at: Norwegian University of Science and Technology (NTNU), Department of Architectural Design, History and Technology, NO-7491 Trondheim, Norway. Tel.: +47 46830077; fax: +47 73595083.
*E-mail address:* ihara.takeshi@takenaka.co.jp (T. Ihara).

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With regards to the design factors, building configuration with fixed envelope properties has been investigated as a factor affecting the heating and cooling energy requirements in a residential space of Rome and Hong Kong [6,7]. As an example of using the facade properties, the reflectance of roofs has been specifically aimed at reducing the cooling energy requirements by minimizing the solar energy gain in the relatively warm and hot regions of the US [8–11]. Facades with a relatively high reflectance of a room composed of specific components have also been discussed in not only hot and warm regions such as Hong Kong and China but also cold regions such as Sweden [12–15]. The emphasis on reflectance has been prompted by the development of highly reflective materials [16–20] that are capable of reflecting greater amounts of near infrared (NIR) solar radiation without the need to change the surface color. The properties of windows significantly affect the energy performance of a building owing to two factors, namely, their relatively high *U*-value compared with the opaque parts and their solar heat gain moderated by glazing systems. A desirable window-to-wall ratio (WWR) has been given from the perspective of minimizing the sum of cooling, heating, and lighting energy demands, assuming a facade property set with a controlled shade of an office space in Germany, the US, and the Netherlands [21–23]. Thermally insulated windows of a building have attracted attention in cold countries owing to their high *U*-values compared with the insulated opaque parts [1]. Transparency is another important factor to maximizing the usage possibility of daytime lighting [24]. Conversely, in the warm parts of Europe, a lower window *U*-value has increased the cooling energy requirements of a stipulated room [25]. In the warm parts of Asia, a few studies have investigated the relationship between energy savings and the properties of advanced windows and shown that windows with low *U*-values (e.g., triple glazing windows) reduce energy consumption in some regions [26]. By focusing on windows of a fixed shape building in India and China, a few studies have also shown that reducing the *U*-value and SHGC could contribute to reducing the sum of cooling and heating demands [27,28]. The *U*-value of the opaque parts of a building is likewise an important factor. Well-insulated walls often save energy, although they tend to be expensive. The optimum insulation thickness of a space was given from the payback period for a given insulation type and thickness [29–31]. The energy saving effect of external insulation, due mainly to nonthermal bridging, has been noted in various regions (e.g., Greece), although the cost of insulation increases [32]. By focusing on an office building with a floor plan, another study has shown that walls with thick insulation do not always enable energy savings in some cities of China [33].

The purpose of this study was to investigate the facade properties that affect energy performance for reducing energy demands for a wide range of office buildings in Tokyo, Japan. This was done by dynamic simulations using the simulation tool WUFI Plus [34]. The considered facade properties were the solar reflectance of the opaque parts of the facade, the *U*-value of the externally/internally insulated opaque parts of concrete walls, the *U*-value of the windows, and the SHGC of the windows. There are numerous energy saving solutions that can be applied to the facade components of buildings, and the focus of this study was the static components; dynamic components such as blinds and electrochromic glazing systems were not considered. The building form, volume, and window-to-wall ratio were also varied. Such combinations of factors have not been investigated in previous studies. The facade properties were varied to determine how each affected the heating and cooling energy consumption. Facade properties do not affect energy demands independently. Nonetheless, this study varied the facade properties, aiming to provide a rule-of-thumb approach for understanding the impact of facade components on heating and cooling energy demands of buildings with various designs. Based on the results, this study proposes measures for saving energy in office buildings in Tokyo through the variation in the facade properties and the building design parameters. A previous study showed that heating and cooling energy consumptions account for approximately 45% of total energy consumption of an office building in Japan [35]. This study therefore focused on heating and cooling demands.

## 2. Methodology

Both heating and cooling energy simulations were performed by varying the facade properties and building design factors. An analysis was used to determine how each facade property affected the annual energy savings.

### 2.1. Annual energy simulation

The annual energy consumption simulation was conducted using the simulation tool WUFI Plus, which is capable of computing the heating and cooling energy demands in buildings with various types of envelopes in Tokyo [34]. WUFI Plus has been experimentally validated by Antretter et al. [36] for a simulation period of one year. Our study used the weather data shown in Fig. 1, titled Standard Expanded AmeDAS Weather Data, 1995 Version, authorized by the Architectural Institute of Japan.

Using the conditions described below, the cooling and heating energy demands were simulated and the annual energy was calculated by summing up both energy demands.

#### 2.1.1. Parameters

According to the ASHRAE standard, Tokyo is categorized as a Zone 3 cooling-dominated area [37], where the main facade design strategies are aimed at controlling solar radiation and reducing external heat gain using well-insulated opaque parts or shading devices, and natural ventilation and light sources are exploited [38]. Table 1 lists the parameter combinations for the annual energy demand simulation, wherein nine parameters were considered, comprising four related to design issues and five related to facade properties.

(1) Number of floors, floor area, and floor aspect ratio

The design factors are normally determined by the surroundings (e.g., road connectivity, environmental conditions, and maximum allowable building volume), and they affect the energy consumption. The geometrical parameters such as the number of floors, floor area, and floor aspect ratio were therefore considered, as listed in Table 2. These parameters are the fundamental factors

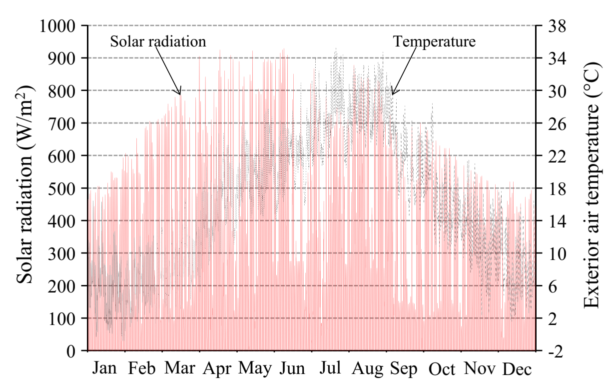


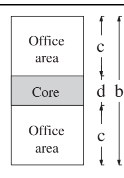
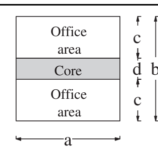
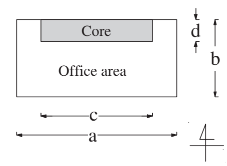

**Fig. 1.** Exterior weather in Tokyo. The solar radiation is the sum of the diffusive and direct solar radiation on a horizontal plane.

**Table 1**
Parameter combinations for annual energy demand simulations. WWR is defined as the ratio of the total window area to the total exterior wall area.

| No. | Design factors | | | | Facade properties | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Number of floors (–) | Floor area ($m^2$) | Floor aspect ratio (–) | Window-to-wall ratio (–) | Solar reflectance of opaque parts (–) | *U*-value of exterior insulated opaque parts (W/($m^2$ K)) | *U*-value of interior insulated opaque parts (W/($m^2$ K)) | *U*-value of windows (W/($m^2$ K)) | SHGC of windows (–) |
| | 5 | 1225 | 0.49 | 0.18–0.21 | 0.1 | 1.003 | 1.003 | 1.2 | 0.09 |
| | 15 | 2401 | 1.00 | 0.09–0.11 | 0.4 | 0.631 | 0.631 | 2.3 | 0.41 |
| | 30 | 3969 | 2.04 | 0.36–0.42 | 0.7 | 0.362 | 0.362 | 4.6 | 0.68 |
| 1 | ○ | ○ | ○ | ○ | ○ | – | – | – | – |
| 2 | ○ | ○ | ○ | ○ | – | ○ | X | – | – |
| 3 | ○ | ○ | ○ | ○ | – | X | ○ | – | – |
| 4 | ○ | ○ | ○ | ○ | – | – | – | ○ | – |
| 5 | ○ | ○ | ○ | ○ | – | – | – | – | ○ |

○: Three variables are considered.
–: Median value for each parameter is used.
X: Not considered.

**Table 2**
Geometries of simulation models.

| Floor aspect ratio | | | 2.04 | | | 1.00 | | | 0.49 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Geometry | Diagram | |  | | |  | | |  | | |
| | Dimensions (m) | a | 24.5 | 34.3 | 44.1 | 35.0 | 49.0 | 63.0 | 50.0 | 70.0 | 90.0 |
| | | b | 50.0 | 70.0 | 90.0 | 35.0 | 49.0 | 63.0 | 24.5 | 34.3 | 44.1 |
| | | c | 20.0 | 28.0 | 36.0 | 14.0 | 19.5 | 24.5 | 35.0 | 49.0 | 45.0 |
| | | d | 10.0 | 14.0 | 18.0 | 7.0 | 10.0 | 14.0 | 730 | 10.0 | 17.6 |
| Floor area ($m^2$) | | | 1 225 | 2 401 | 3 969 | 1 225 | 2 401 | 3 969 | 1 225 | 2 401 | 3 969 |

considered in the building design phase. This study used whole building models because it aimed to determine facade properties that affect energy performance for a wide range of design factors of a whole building. In all the models used, the main facade of the building faced south and the building orientation was north–south. All the simulated buildings had rectangular floors, with the low-rise buildings comprising ~5 floors and the high-rise buildings ~30 floors. The floor area was determined from the scale of the building plan. A number of floors were added to the floor plan as simulation parameters to determine the building volume. With regard to the floor plan, it was not possible to represent all possible building shapes. Nevertheless, the considered parameters were sufficient to obtain fundamental ideas about how the facade components affect the annual energy usage. The office area and the core were considered to define the window fenestration distribution. The office area was set to ~80% of the floor area for each model, and the core was assumed to comprise stairs, elevators, and common spaces (e.g., hallways, restrooms, and meeting rooms). The details of each core plan were not considered.

(2) Window-to-wall ratio (WWR)

Table 3 lists the three types of fenestration configurations assumed for each floor plan. One of the design factors that were considered to affect the energy demand was the WWR, which was defined as the ratio of the total window area to the total exterior wall area. For each floor level, two fenestration configurations were assumed for the office area and core, respectively. The window distribution was determined by each floor plan as defined in Table 2. In this study, the WWR was varied between approximately 0.1 and 0.4. The core was assumed not to have any windows. The height of each floor was set to 4 m.

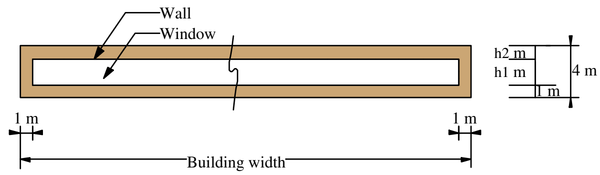
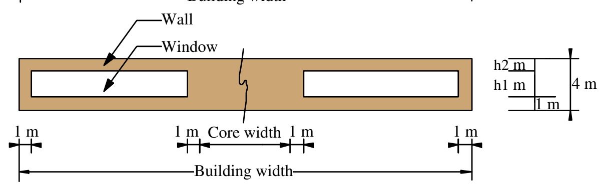
(3) Solar reflectance of opaque parts and *U*-value of exterior and interior insulated opaque parts

Three parameters of the opaque parts of the facades were considered. The opaque parts were also defined by the design factors. In this study, the section of the opaque part of the facades was assumed to be as shown in Fig. 2.

The solar reflectance of the opaque parts was considered as a parameter, and the value for the outermost surface was varied between 0.1 and 0.7 in steps of 0.3, with the thermal emissivity set at a constant value of 0.9. The envelopes of buildings often incorporate metal layers, which are chosen from the viewpoint of construction efficiency or architectural beauty. These metal layers are usually thin and may attain high temperatures during the daytime. In warm areas, high temperatures of the surface of building materials are undesirable because they may cause the heat island phenomenon, which increases cooling requirements. A metal wall with an aluminum panel was therefore modeled, as shown in Fig. 2. The section composition of the wall was typical of the external metal wall of buildings in Japan. A 1D model was used in this study. During the model construction, spotted metal frames or successive straight metal frames were used to fasten the aluminum panels. The latter tends to produce more thermal bridges than the former, and the metal frame was therefore not considered in the simulation. Similarly, a gypsum board as the interior material accompanied an adjacent layer (air layer 2).

The *U*-values of the opaque parts were varied between 1.003 and 0.362 W/($m^2$ K) by changing the insulation thickness at either the interior or exterior of the concrete layer. Polyurethane (PUR) was assumed as the thermal insulation material, and *U*-values of 1.003, 0.631, and 0.362 W/($m^2$ K) were applied to the model, and insulation thicknesses of 10, 30, and 70 mm, respectively. Table 4

**Table 3**
Fenestration configurations of simulation models.

| | Facade fenestration configuration | | |
|---|---|---|---|
| Elevation of an office area |   | | |
| Elevation of a core side |   | | |
| WWR | 0.38–0.42 | 0.18–0.21 | 0.09–0.11 |
| h1 | 2.0 | 1.0 | 0.5 |
| h2 | 1.0 | 2.0 | 2.5 |

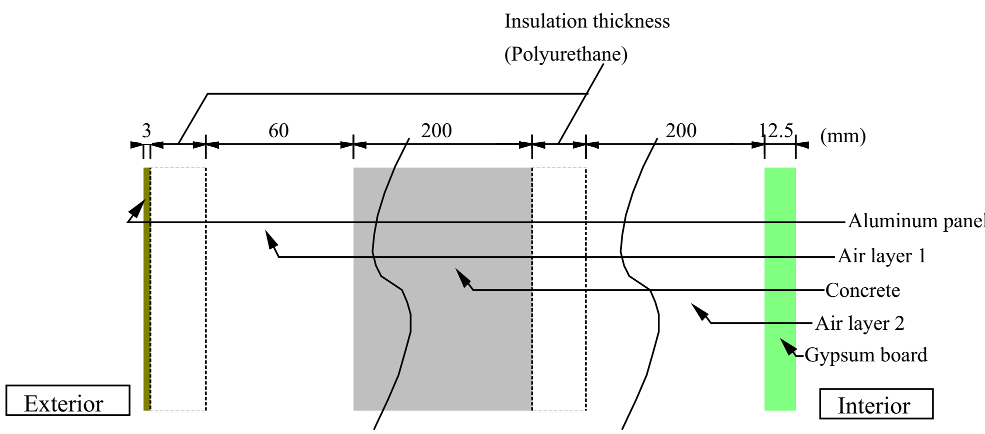



**Fig. 2.** Wall section of simulation models.

**Table 4**
Material properties of wall. Data is available in [34].

| Material | Density (kg/m$^3$) | Specific heat capacity (J/(kg K)) | Thermal conductivity (W/(mK)) | Total surface heat transfer resistance (m$^2$ K/W) |
|---|---|---|---|---|
| Outdoor surface | – | – | – | 0.04 |
| Aluminum | 2700 | 920 | 174 | – |
| Air layer 1 | 1.3 | 1000 | 0.337 | – |
| Concrete | 2300 | 850 | 1.6 | – |
| Polyurethane | 40 | 1500 | 0.03 | – |
| Air layer 2 | 1.3 | 1000 | 1.213 | – |
| Gypsum board | 732 | 1384 | 0.193 | – |
| Indoor surface | – | – | – | 0.13 |

lists the material properties [39]. The thermal conductivities of the air layers were considered to involve a convection effect with respect to the layer width because space was allowed for the metal backing frames. The air thermal conductivities were thus larger than the intrinsic value for stagnant air (~0.026 W/(mK) [40]). The input air thermal conductivities were applied by referencing the simulation tool database [34], which contained a thickness range of 5–150 mm, and the thermal conductivity of air layer 2 was determined by extrapolation.

(4) *U*-value and SHGC of windows

The *U*-value and SHGC of the windows are important parameters that influence the heating and cooling energy demands of a building. In this study, the *U*-values of the windows were varied between 1.2 and 4.7 W/(m$^2$ K), and values of 1.2, 2.3, and 4.7 W/(m$^2$ K) were assumed for triple, double, and single glazing systems, respectively. Double glazing systems are currently most

**Table 5**
Details of applied SHGCs.

| Hemispherical SHGC | Incidence angle (°) | | | |
|---|---|---|---|---|
| | 0 | 30 | 60 | 80 |
| 0.09 | 0.496 | 0.098 | 0.090 | 0.051 |
| 0.41 | 0.473 | 0.467 | 0.395 | 0.159 |
| 0.68 | 0.780 | 0.773 | 0.661 | 0.263 |

commonly used. Current commercially available windows have a better thermal performance than those used in the simulation of this study. The total window *U*-values are normally higher than the center-of-glazing *U*-values because of the frame and connection between glazing and frame. Therefore, the input of window *U*-values were selected to be slightly higher than those of commercially available glazing systems. The shading produced by the window frames was not considered in determining the effect of the SHGC of the windows on the annual energy demand. The SHGC of the windows was varied between 0.09 and 0.68. Table 5 gives the assumed details of the hemispherical and directional SHGCs. The values were obtained from data acquired by the simulation tool WINDOW [41], which can be used to calculate the optical and thermal properties of glazing/window systems. Based on the WINDOW calculations, hemispherical SHGCs of 0.09, 0.41, and 0.68 were assumed for double glazing comprising a float glass and a black polyvinyl butylal laminated pane, double glazing comprising a float glass and a low-E coating pane, and double glazing comprising two float glasses, respectively. The SHGC depends on the incidence angle of the solar radiation, and the values for the four angles given in Table 5 were considered in the simulation.

#### 2.1.2. Fixed variables

Table 6 lists the properties of the other building components such as the ground floor, intermediate floors, and roof. Each component composition was typical of that used in Japanese office buildings. The thermal emissivity and solar reflectance of the roof surface were both set to 0.8, and those of the intermediate floors and other finishing materials (i.e., the raised access floors and ceiling boards) were ignored because such components were not considered hermetic. Each value was applied by referencing the simulation tool database.

Tables 7–9 list the indoor loads and the assumptions of the indoor climate and heating, ventilation, and air conditioning (HVAC) designs. The maximum values of the HVAC design specifications were the typical values for Japanese office buildings. The mechanical ventilation worked to control relative humidity within 50–60% RH. The annual heating and cooling energy demands were the focus on in this study. Therefore, the difference between heating and cooling systems was not considered, and a coefficient of performance of 1.0 was used for the systems. The mechanical ventilation indicated in Table 8 activated when the level of carbon dioxide in the simulated zone model exceeded 1000 ppm owing to presence of people, thus affecting the heating and cooling energy demands.

## 3. Results and discussion

The simulation results are presented and discussed in this section. During the examination of a specific facade parameter, all the other parameters were maintained at their median values (see Table 1), and this applies to all the figures in this section.

### 3.1. Annual energy simulation

#### 3.1.1. Effect of solar reflectance of opaque parts

Fig. 3 shows some effects of the solar reflectance of the opaque parts. In all the simulated buildings, when the solar reflectance was increased, the cooling energy demand decreased owing to the reduced heat transmittance resulting from the lower surface temperature; however, the heating energy demand increased owing to the reduced heat gain from the exterior walls. The cooling energy demand accounted for 55.8–99.9% of the total cooling and heating energy demand.

The decreased cooling energy demand was slightly higher than the increased heating energy demand in all the simulations. Consequently, all the calculation results indicated slightly reduced annual energy demand with increasing solar reflectance. The reduction was not significant in any of the simulations. When the solar reflectance was increased from 0.1 to 0.7, the decrease in the annual energy demand was 0.4–3.4% for a five-floor building, 2.0–5.8% for a 15-floor building, and 2.0–9.4% for a 30-floor building. Furthermore, the reduction in the annual energy demand

**Table 6**
Properties of fixed building components.

| Building component | Properties | | | | | | |
|---|---|---|---|---|---|---|---|
| | Material | *U*-value (W/(m$^2$ K)) | Thickness (m) | Density (kg/m$^3$) | Specific heat capacity (J/(kg K)) | Thermal conductivity (W/(mK)) | Total surface heat transfer resistance (m$^2$ K/W) |
| Ground floor | Outdoor surface | 1.99 | – | – | – | – | 0.00 |
| | Concrete | | 0.5 | 2 300 | 850 | 1.6 | – |
| | Mortar | | 0.01 | 1 568 | 488 | 0.484 | – |
| | Indoor surface | | – | – | – | – | 0.17 |
| Intermediate floor | Outdoor surface | 3.39 | – | – | – | – | 0.17 |
| | Concrete | | 0.2 | 2 300 | 850 | 1.6 | – |
| | Indoor surface | | – | – | – | – | 0.17 |
| Roof | Outdoor surface | 0.86 | – | – | – | – | 0.04 |
| | Concrete | | 0.06 | 2 300 | 850 | 1.6 | – |
| | Expanded polystyrene | | 0.035 | 30 | 1 500 | 0.04 | – |
| | Bituminous membrane | | 0.002 | 2 400 | 1 000 | 0.5 | – |
| | Concrete | | 0.2 | 2 300 | 850 | 1.6 | – |
| | Indoor surface | | – | – | – | – | 0.10 |

**Table 7**
Indoor loads.

| Indoor load | Weekdays | | Weekends | Assumption |
|---|---|---|---|---|
| | 09.00–17.00 | 17.00–21.00 | 09.00–17.00 | |
| Occupant density (person/m$^2$) | 0.1 | 0.03 | 0.003 | Adult sitting at work |
| Technical equipment (W/m$^2$) | 26 | 8 | 0.78 | Lighting, computer, etc. |

**Table 8**
Assumptions of indoor climate design.

| Parameter | | Assumption |
|---|---|---|
| Maximum temperature for cooling (°C) | 25 | Constant value during 1 year |
| Minimum temperature for heating (°C) | 22 | Constant value during 1 year |
| Maximum relative humidity for dehumidification (% RH) | 60 | Constant value during 1 year |
| Minimum humidity for humidification (% RH) | 50 | Constant value during 1 year |
| Mechanical ventilation ($m^3/(m^2h)$) | 2.5 | Controlled based on temperature (no natural ventilation) |
| Air change rate through infiltration (1/h) | 0.1 | – |
| Maximum concentration of carbon dioxide (ppm) | 1000 | – |

**Table 9**
Assumptions of heating, ventilation, and air conditioning (HVAC) design.

| Parameter | Weekdays | | Weekends | Assumption |
|---|---|---|---|---|
| | 08.00–17.00 | 17.00–21.00 | 09.00–17.00 | |
| Heating system power ($kW/m^2$) | 0.110 | 0.036 | 0.110 | All indoor areas are heated or cooled. No time delay between zero |
| Cooling system power ($kW/m^2$) | 0.140 | 0.046 | 0.140 | and maximum heating power. |
| Mechanical ventilation ($m^3/(m^2h)$) | 2.5 | 0.75 | 0.075 | Efficiency of heat recovery is 80%; that of moisture recovery is 0%. |

with increasing solar reflectance was more pronounced for the low-WWR models than for the high-WWR models. In other words, a building with larger opaque facade parts affected the annual energy usage more. For 15–30 floors, no large energy demand difference was observed among the three floor aspect ratios. This indicated that a large-volume building was not affected by its orientation from the viewpoint of the wall reflectance. For all the simulations, an almost linear relationship was observed between the solar reflectance and the reduction in the annual energy demand. The energy saving may be achievable without increase in cost by, for example, changing the color of the facade. Hence, the solar reflectance of the opaque parts of a Tokyo building does not always significantly affect the annual energy demand; nevertheless, a slightly reduced energy demand could be expected. It

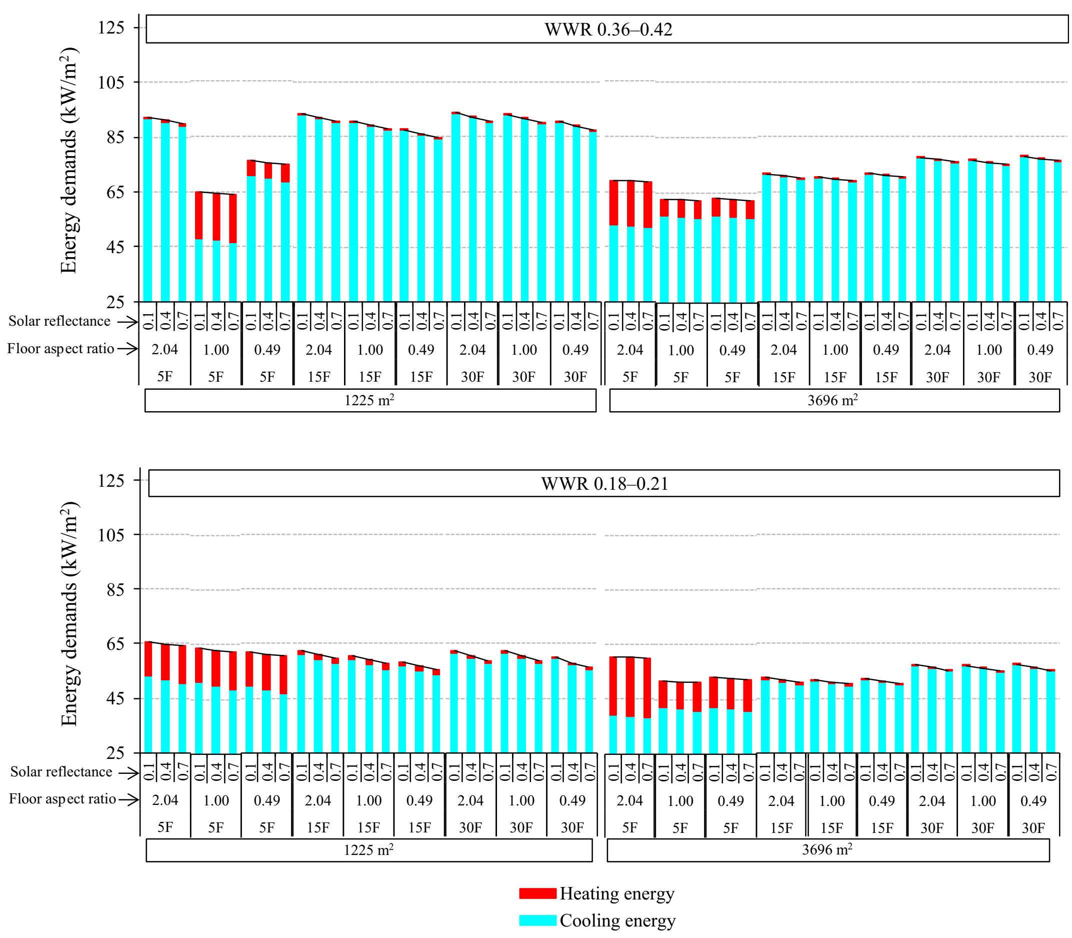



**Fig. 3.** Sample curves of annual energy demand versus solar reflectance determined by simulation for buildings in Tokyo, Japan. The following is valid for this figure and Figs. 4–7: the WWR for each number of floors was slightly varied by varying the window fenestration, which depends on the floor aspect ratio (see Table 3).

is therefore preferable to maximize the facade solar reflectance to enhance the energy efficiency. Reflected radiation might adversely affect the comfort of pedestrians in nearby streets and residents in adjacent buildings.

### 3.1.2. Effect of U-value of interior insulated opaque parts

Fig. 4 shows some effects of the *U*-value of the interior insulated opaque parts. The cooling energy demand amounted to 52.8–99.9% of the total cooling and heating demand. For most models with five floors, a large decrease in heating energy demand and a slight increase in cooling energy demand were observed with decreasing *U*-value, and thus the annual energy demand decreased. For most of the models with 15 and 30 floors, a lower *U*-value increased the cooling demand, whereas the heating energy demand decreased slightly. The former is larger than the latter, and therefore the annual energy demand increased with a lower *U*-value.

The five-floor models tended to be more susceptible to heat transmittance through the roofs than the 15- and 30-floor models. The total volume of intermediate concrete slabs may be another reason; greater solar energy gain to the interior due to the concrete might increase cooling demand for the 15- and 30-floor models. The floor aspect ratio of the five-floor models therefore significantly affected the energy demand. Some of the results suggested the existence of an optimal *U*-value that minimized the energy demand for each model; for example, in the case of WWR of about 0.1 for a 15-floor building in Fig. 4. The relationship between the *U*-value and the annual energy demand was not always linear.

It was difficult to determine the relationships between the design factors and the *U*-value from the simulation results. An important observation was that the annual energy demand increased with decreasing *U*-value in most of the simulations. Walls with suitable *U*-values are thus recommended for cooling-dominated high-rise buildings. The composition of the wall is often determined by aesthetic and structural considerations during the design, and the energy demand might be increased if the *U*-value is not adequately considered. Proper ventilation design is also important in cooling-dominated buildings. Energy saving may be ensured by a suitable *U*-value achieved by appropriate thermal insulation and wall composition. The obtained results revealed that some smaller buildings such as five-floor buildings may require better insulation than larger buildings such as 15- and 30-floor buildings owing to the greater energy saving potential of the former.

### 3.1.3. Effect of U-value of exterior insulated opaque parts

The exterior insulated opaque parts generally utilize the heat storage effect because the concrete structure, which has a higher heat capacity, is exposed to the indoor zone. This effect is examined below using the results shown in Fig. 5. The cooling energy demand constituted 52.7–99.9% of the total cooling and heating energy demand. In most of the simulation cases, when insulated parts were changed from the interior to the exterior, the annual energy demand was reduced by 0.1–7.2 kW h/m$^2$. For most of these cases, the results showed that heating and cooling energy

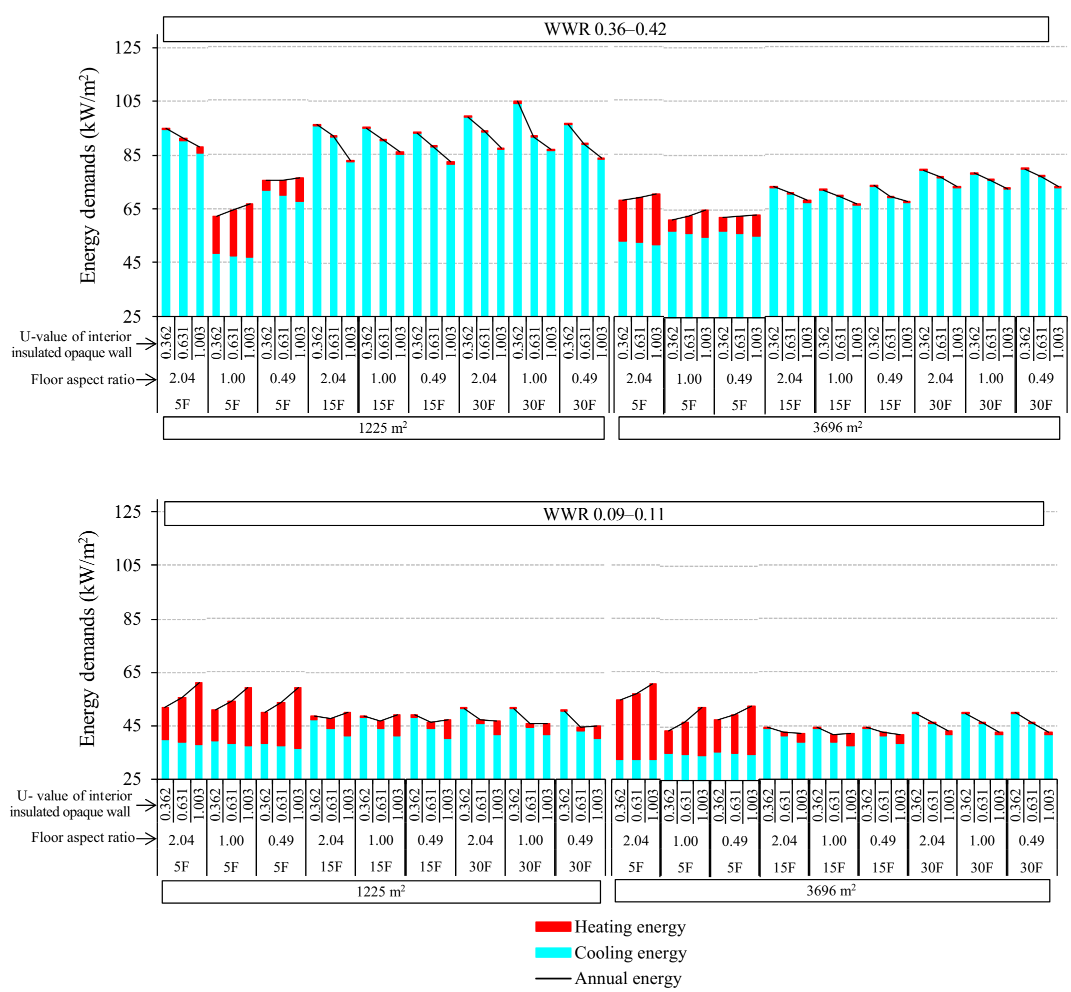



**Fig. 4.** Sample curves of annual energy demand versus *U*-value of interior insulated opaque parts determined by simulation for buildings in Tokyo, Japan. For further explanation, refer to Fig. 3.

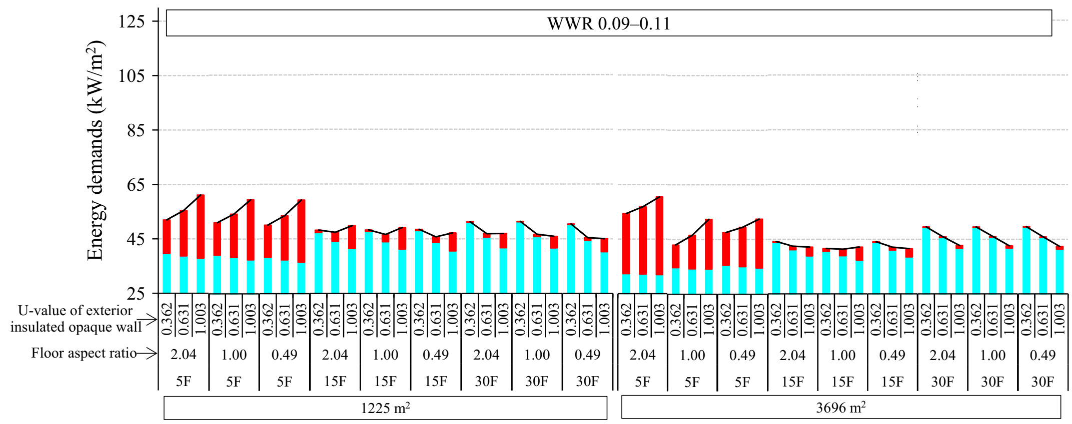



**Fig. 5.** Sample curves of annual energy demand versus *U*-value of exterior insulated opaque parts obtained by simulation for buildings in Tokyo, Japan. For further explanation, refer to Fig. 3.

demands with exterior insulation were lower than those applying interior insulation. In some cases with annual energy demand reduction, the decreased heating energy demand compensated for the increased cooling demand. In several cases, the annual energy demand for exterior insulation was higher by 0.1–4.5 kW h/m$^2$ than that for interior insulation. For these cases, no common reasons were observed. Heating energy demand, cooling energy demand, or both, became higher after changing the insulation location from interior to exterior.

Therefore, exterior insulation only slightly improved the energy saving compared with interior insulation. The intermediate slab may be considered as a heat storage element, and the heat storage in the wall may therefore not be critical to energy saving. It may be more feasible to achieve sufficiently low *U*-values in many office buildings by interior insulation because of the lower cost compared with exterior insulation. It should, however, be noted that it is easier to achieve a facade without thermal bridges by using exterior insulation.

### 3.1.4. Effect of U-value of windows

Fig. 6 shows some effects of the *U*-value of the windows. The cooling energy demand accounted for 54.0–99.9% of the total cooling and heating energy demand. A significant reduction in the energy demand with decreasing *U*-value was observed in each

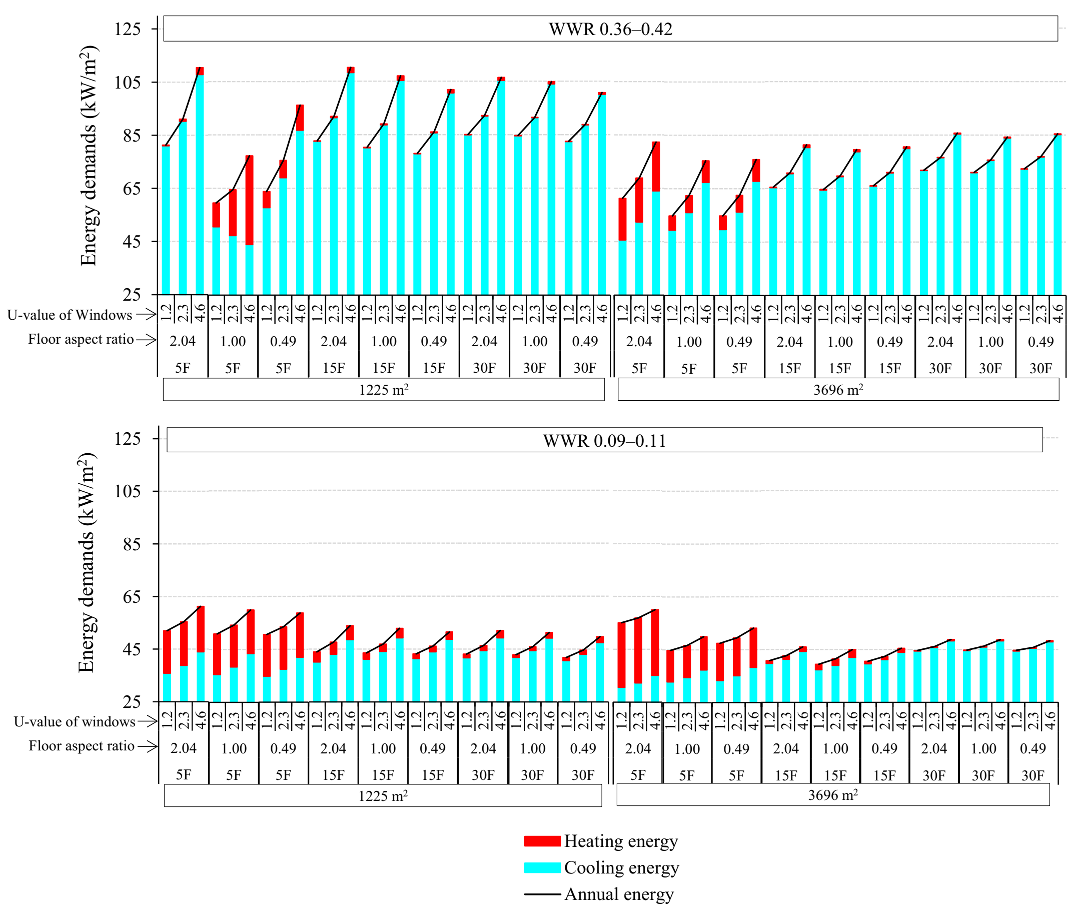



**Fig. 6.** Sample curves of simulated annual energy demand versus window *U*-value obtained by simulation for buildings in Tokyo, Japan. For further explanation, refer to Fig. 3.

case. A lower window *U*-value tended to result in energy saving by decreasing the cooling and heating energy demand. The relationship between the window *U*-value and the annual energy demand was nearly linear for all the considered cases. The effect of the *U*-value was also determined by the WWR, with a smaller WWR reducing the gradient of the variation in the annual energy demand with the *U*-value. For a five-floor building, the annual energy demand varied significantly with the floor plan ratio, whereas there was little variation for 15- and 30-floor buildings. When the window *U*-value was decreased from 2.3 to 1.2 W/(m$^2$ K), the reduction in the annual energy was 3.2–15.5% for five-floor buildings, 0.1–11.1% for 15-floor buildings, and 2.3–8.3% for 30-floor buildings. Buildings with lower window *U*-values thus exhibited enhanced energy efficiencies.

As the previous sections discussed, reduction in the *U*-value of opaque parts mostly resulted in an increase in the annual energy demand. An explanation for this might be that the opaque parts had the *U*-value in the range of 0.362–1.003, whereas the *U*-value of the windows-in was 1.2–4.6. Further research should be conducted to investigate the window *U*-value limitation from an energy point of view.

Windows with low *U*-values of ~1.2 W/(m$^2$ K) (e.g., triple glazing windows) are not commonly used in Asian countries, including Japan. System-level solutions such as double skin facades and air flow windows are instead employed owing to their higher energy and construction efficiencies as well as aesthetics. However, the simulation results of the present study suggest that low-*U*-value windows may improve the energy efficiency. Low *U*-values may be achieved by commercially available material-level solutions such as multi-pane glazing systems, aerogel glazing systems, and well-insulated frames. Such solutions enable more robust construction than system-level solutions and should therefore be considered.

### 3.1.5. Effect of SHGC of windows

Fig. 7 shows some effects of the SHGC of the windows. The cooling energy demand accounted for 47.3–99.9% of the total cooling and heating energy demand. A reduction in the SHGC decreased the cooling demand but increased the heating demand, with the change in the former greater than that in the latter. All the calculations thus produced reduced annual energy demand. The solar energy gain through the windows was significantly affected by the WWR. When the SHGC was varied, a smaller window area had a less effect in reducing the annual energy demand than a larger window area. For larger window areas (WWR = 0.36–0.42), when the SHGC was decreased from 0.68 to 0.09, the annual energy demand was nearly halved in some cases, as shown in Fig. 7. For smaller window areas (WWR = 0.08–0.11), the annual energy demand gradually decreased with decreasing SHGC. In all cases, the annual energy demand decreased with decreasing SHGC. When the SHGC was decreased from 0.68 to 0.41, the decrease in the annual energy demand was 0.8–24.1% for five-floor buildings, 1.0–25.9% for 15-floor buildings, and 8.6–25.3% for 30-floor buildings. The reduction in the SHGC thus significantly decreased the annual energy demand. In addition, the annual energy demand varied with the floor aspect ratio for a five-floor building, whereas there was little variation for 15- and 30-floor buildings. The relationship between the SHGC and the annual energy demand was

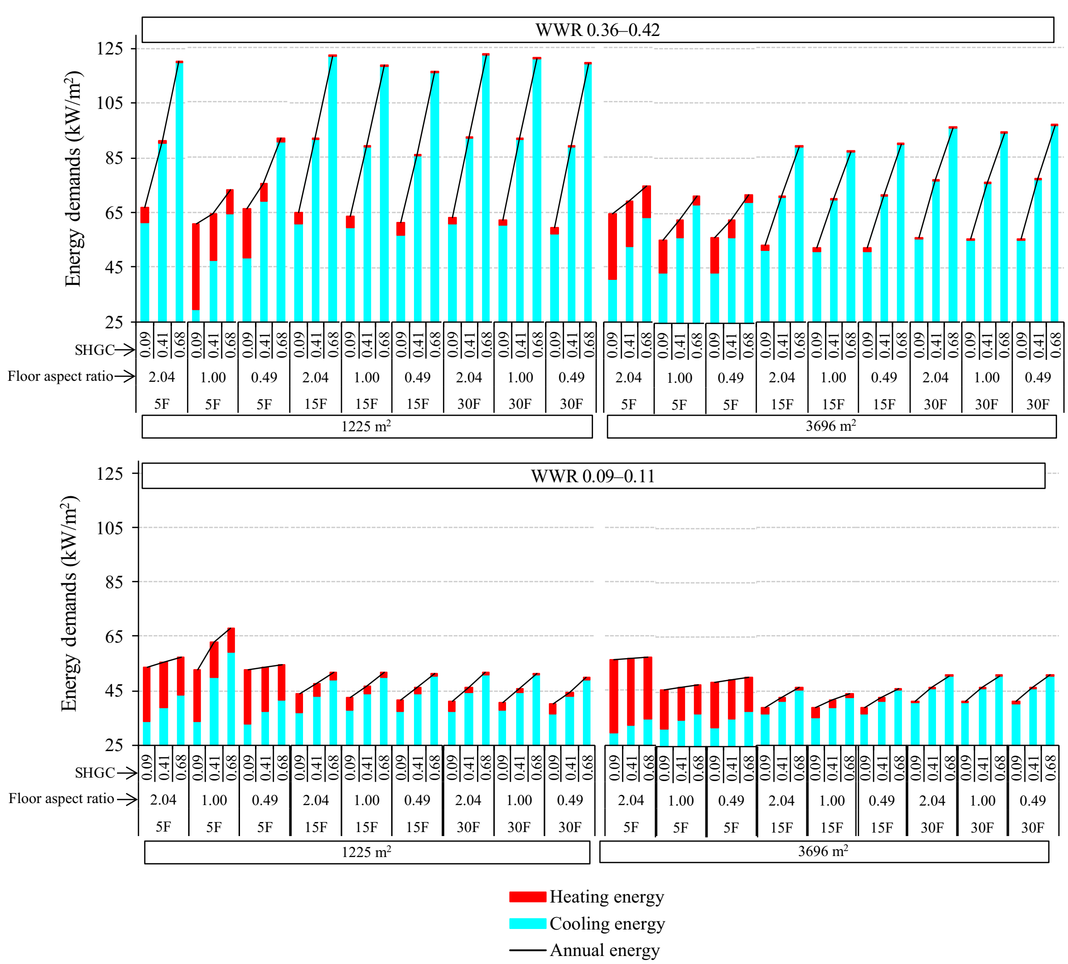



**Fig. 7.** Sample curves of annual energy demand versus SHGC obtained by simulation for buildings in Japan, Tokyo. For further explanation, refer to Fig. 3.

**Table 10**
Effects of facade properties of Tokyo buildings on reduction of annual energy demand as determined from simulation results (see Table 1 and Figs. 3–7).

| Facade solution | Range of annual energy demand reduction | | |
|---|---|---|---|
| | 5-floor building | 15-floor building | 30-floor building |
| Reduction in solar reflectance of walls by 0.1 within range of 0.1–0.4 | 0.05–0.59% | 0.35–1.00% | 0.28–2.15% |
| Reduction in *U*-value of exterior wall insulation by 0.1 W/(m$^2$ K) within range of 1.003–0.631 W/(m$^2$ K) | −0.98–3.01% | −1.82–1.38% | −2.53–0.05% |
| Reduction in *U*-value of interior wall insulation by 0.1 W/(m$^2$ K) within range of 1.003–0.631 W/(m$^2$ K) | −1.01–2.95% | −2.98–1.27% | −2.53–0.32% |
| Reduction in window *U*-value by 0.1 W/(m$^2$ K) within range of 1.2–2.3 W/(m$^2$ K) | 0.29–1.41% | 0.13–1.01% | 0.21–0.75% |
| Reduction in window SHGC by 0.1 within range of 0.09–0.41 | 0.26–7.53% | 1.81–8.08% | 2.69–7.90% |

almost linear for most of the cases. (This study did however not consider lighting energy demands, which will vary along the facade of the buildings. This should be considered in future studies.) The selection of an appropriate SHGC may thus be used to achieve large energy savings. The SHGC also affects the daytime lighting energy demand and certain human psychological factors such as indoor comfort. SHGC reduction therefore does not constitute a universal energy solution. The SHGC should be fixed during the building design using different methods such as architectural adjustments (e.g., changing the wall area with respect to the direction and using receding windows and protruding outer pillars), using shading devices (e.g., awnings and blinds), and applying material technologies (e.g., electrochromic glazing systems [1,42], solar cell glazing systems [1,43], and aerogel glazing systems [1,5]).

### 3.2. Effects of facade properties

The facade properties and design factors dependently affect the energy demand. Nevertheless, the effects of the facade properties were evaluated under the simulation conditions given in Table 1. The ranges of the annual energy demand reduction determined from the simulation results are given in Table 10. The annual energy demand reductions given in the table are those achieved by varying the facade properties. The ranges of the annual energy demand were calculated by assuming linear relationships between the facade properties and the annual energy demand reduction. It is thus possible to determine which facade property can be used to achieve significant energy reduction. The solar reflectance, window *U*-value, and SHGC enable reduction in the energy demand regardless of the volume of the building, the orientation, and the WWRs. Among these three properties, the SHGC enabled the largest energy reduction, and the solar reflectance the lowest. Conversely, the reduction in the *U*-value of the opaque parts increased the annual energy demands of most of the high-rise buildings, although energy saving by reduction in the *U*-value could be expected in some low-rise buildings. It is therefore necessary to appropriately set the *U*-value of the opaque parts of a building during the design. Proper ventilation design is also important in the cooling-dominated buildings.

The overall results of our study enable the determination of the facade property that should be focused on during the design of a building. In a future work, combined variation in facade properties will be considered, as well as the inner heat loads and occupancy of the building. The details of the energy demands, such as the cooling and heating demands in different parts of the building, are also subjects requiring further study. The present study afforded a means for quick determination of the effects of different facade components on the annual heating and cooling energy requirements of a building.

## 4. Conclusions

For facade materials in a wide range of applications, facade properties that strongly affect building energy performance regardless of building shapes and scales should be considered. An approach for determining the effects of different facade components on energy saving in an office building in Tokyo, Japan, using certain assumptions was investigated in this study. The solar reflectance, *U*-value of the opaque parts, *U*-value of the windows, and solar heat gain coefficient (SHGC) of the windows were the considered facade properties. SHGC reduction was found to be the most effective means of reducing the annual energy demand, followed by reduction in the window-U value, and then increase in the solar reflectance. These three approaches could be used to reduce the annual energy demand regardless of design factors such as the building volume, floor aspect ratio, and window-to-wall ratio. Hence, window innovations such as multi-pane windows, insulated window frames, and shades may be variously employed as solutions. Using a higher reflectance may also be considered as an inexpensive solution. Conversely, the reduction in the *U*-value of the opaque parts was observed to increase the annual energy demand of most high-rise buildings, although this enabled energy saving in some low-rise buildings. It is therefore necessary to apply the appropriate opaque part *U*-value during the design of a building.

The findings of the present study may be useful for development of new facade materials and components aimed at an energy-efficient building, considering the difficulties posed by the relationship between facade properties and design considerations. Future research should consider other factors that affect energy performance (e.g., other combinations of facade properties, behavior, building types, and dynamic facade properties) based on the findings of the presented study.

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