# Energy and Daylighting Performance of Senior Housing

Performance evaluation of a senior apartment in China

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***Abstract*—Senior living facilities consume more energy than other types of residential buildings due to seniors' different lifestyles and comfort levels. In order to reduce the high energy consumption of senior living facilities, designers should consider sustainable design strategies. One important strategy is daylighting because of its potential to save energy and to benefit seniors' health. This paper presents a case study based on a senior apartment in Changsha, China. Simulation models are developed to analyze the building's energy consumption and daylighting conditions. Simulation input parameters are adopted through a literature survey to accommodate the real lifestyles and thermal comfort conditions of seniors. Daylight levels are tested, analyzed and considered in relation to energy performance. This paper shows that daylighting is a more efficient energy saving measure for senior living facilities than it is for regular residential buildings.**

***Keywords-senior housing; thermal comfort; visual comfort; energy saving; daylighting.***

## I. INTRODUCTION

The elderly population is growing dramatically worldwide, hence the increasing demand for senior housing and senior-care facilities. The population of the elderly—people aged 60 years or over—is predicted to more than double between 2013 and 2050. Also, the proportion of aged people will increase from 12 percent in 2013 to 21 percent in 2050. The population is aging more quickly in developing countries than in developed countries, and China has one of the fastest-aging populations in the world [1].

As people age, their physical fitness and physiological functions degrade. In order to maintain seniors' comfort levels, special built environments need to be developed, specifically thermal [2], lighting [3], and acoustic environments [4]. However, most building standards and codes that currently govern the physical built environment are based on the needs of younger adults and do not specifically address seniors' requirements.

Senior-care facilities have nearly two times the Energy Use Intensity (EUI) of normal residential buildings [5]. The reason for the enormous EUI should be investigated in order to achieve the energy saving goals in senior housing.

This research studies aspects of a specially built environment, such as room temperature and lighting level, which affect the ability of seniors to maintain their health and comfort. The energy consumption features of senior housing are examined to find how they are different from those of housing for younger adults. The importance of daylighting for seniors and senior housing are proposed. The energy savings though daylighting are assessed through a modified simulation process using the OpenStudio [6], Radiance [7], and EnergyPlus [8] simulation programs.

The second section of the paper reviews the literature about the input values for simulation, which are the temperature and illumination for seniors' comfort. The third section describes the methodology of the research, including the simulation model, simulation tools, and simulation process. The fourth section presents the simulation of four energy models, the fifth section analyzes the simulation results, and the sixth section shows the conclusion of the research.

## II. LITERATURE REVIEW

### A. *Temperature and Thermal Comfort*

Thermal comfort is one of the most important criteria to consider when evaluating a built environment. The temperature setpoint has a huge impact on the building's energy consumption. According to current standards, the comfort temperature requirements are the same for people of all ages. However, researchers have found that the elderly have different thermal environment preferences from younger adults.

In a climate chamber research, it was found that older adults prefer a higher ambient temperature, 23.1 °C (73.5 °F), than do younger adults, 21.9 °C (71.4 °F), for a difference of about 1.2 °C (2.0 °F) [2]. It has also been found that the elderly prefer a higher temperature than do younger adults [9]. A field study about seniors' thermal comfort requirements in residential environments showed that seniors' temperature of thermal neutrality was 25.2 °C (77.4 °F) for the summer and 23.2 °C (73.8 °F) for the winter [10]. However, other studies found different results that older adults preferred the same environmental temperature as the younger adults and that the optimal temperature for thermal comfort was 21.1 °C (70.0 °F) for both age groups [11].

This study is based on the assumption that seniors prefer relatively high temperatures. People's temperature preferences tend to vary according to climate and culture, so data on the specific thermal condition preference of the

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seniors in China would be beneficial to future studies. In this study, the ASHRAE 90.1-2004 standard is used for the baseline simulations. In ASHRAE 90.1-2004, the heating and cooling temperature settings for mid-rise apartment are 21.1 °C (70.0 °F) and 23.9 °C (75.0 °F), respectively. In this study, higher temperature settings are used for the simulation models of senior housing; the heating and cooling temperatures are changed to 22.2 °C (72.0 °F) and 25.0 °C (77.0 °F), respectively.

### B. *Illumination and Visual Comfort*

Lighting energy accounts for an important proportion of building energy consumption. ASHRAE standards normally set the lighting energy based on the Illuminating Engineering Society's (IES) lighting level recommendations for normally-sighted people.

However, because of changes in the human eye lens and the visual nervous system over time, the amount of effective light reaching the retina declines as a person ages. Seniors require about two to three times the light of younger adults to have proper visual acuity and to see comfortably [3]. Therefore, the lighting power density requirements of ASHRAE standards are not adequate for providing sufficient lighting for seniors. Insufficient lighting can cause falling, collision, vision loss, and other problems.

Recently, the IES has developed special lighting requirements for seniors. Table I shows the comparison of the illuminance requirements for senior housing versus the requirements for offices and normal residence environments. Senior housing needs about the same lighting level as offices, and the general lighting requirement is 4 times the illuminance of normal residences.

In this study, a simple approach is used for determining the lighting power density of senior housing. In ASHRAE 90.1-2004, the lighting power density is 3.88 W/m$^2$ (0.36 W/ft$^2$) for mid-rise apartments and 10.76 W/m$^2$ (1 W/ft$^2$) for offices. Because the illuminance requirement of senior housing is similar to that of an office, the lighting power density for senior housing is set to 10.76 W/m$^2$ (1 W/ft$^2$). Only general lighting is considered in this study; task lighting such as dining and reading lighting are not considered.

### C. *Daylighting and Health*

Seniors tend to stay in their homes for more of the day than younger adults, and they need more light to see clearly, so daylighting is a more suitable energy-saving measure for senior housing than it is for other residential buildings. Daylighting also offers great health benefits to seniors.

TABLE I. COMPARISON OF ILLUMINANCE LEVEL [3][12]

| Area | Senior housing [Lux (FC)] | Office [Lux (FC)] | Residence [Lux (FC)] |
|---|---|---|---|
| General lighting | 300 (30) | 300 (30) | 75 (7.5) |
| Dining/Cafeteria | 300 (30) | 300 (30) | 150 (15) |
| Bathrooms | 300 (30) | 150 (15) | 150 (15) |
| Grooming | 600 (60) | NA | 300 (30) |
| Corridors | 300 (30) | 150 (15) | 75 (7.5) |

Daylight exposure can stimulate the production of vitamin D under the skin, improve the health of bones and muscles, and prevent seniors from falling and suffering fractures [3]. As people age, the ability of their skin to produce vitamin D decreases, and they tend to spend less time outdoors [3]. Another possible effect of insufficient or improper lighting is circadian dysfunction, which can lead to Seasonal Affective Disorder (SAD) and Sick Building Syndrome (SBS) [13]. Therefore, sufficient natural light in the rooms is especially important for senior housing. Daylighting design should be an important consideration in senior housing.

## III. METHODOLOGY

### A. *Research Framework*

The study includes the simulation of four energy models with the same building geometry. Figure 1 shows the framework of the research. The first energy model is the baseline model for a regular mid-rise apartment. The second energy model is the baseline model for a senior apartment. The comparison of the first and second models shows how a regular apartment and a senior apartment have different energy performance. The third energy model is the regular apartment with daylighting strategies, and the fourth energy model is the senior apartment with the same daylighting strategies. The daylighting conditions of the models are evaluated, and the energy saving through daylighting is found by comparing the four models. The difference in the energy saving shows how daylighting performs differently in regular housing as compared to senior housing.

### B. *Simulation Tools and Process*

The OpenStudio program, developed by the National Renewable Energy Laboratory (NREL), is used as the primary simulation platform. OpenStudio runs as a plug-in for the SketchUp program that develops three-dimensional geometries. As a graphic user interface, OpenStudio uses the EnergyPlus program, developed by the US Department of Energy, to run thermal simulations, and the Radiance program, developed by the Lawrence Berkeley National Laboratory, to run daylight performance simulations.

Typically, the daylighting simulation workflow in OpenStudio is to first export the building geometry and model data into a rad file for simulation in Radiance. A lighting schedule is generated automatically after the daylighting simulation and is embedded into the OpenStudio

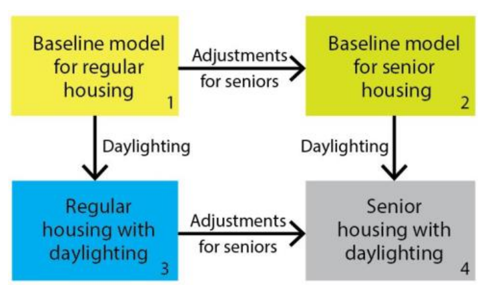


Figure 1. Research Framework

file for final whole-building energy simulation [6]. However, this typical process is not appropriate for the present study. No input adjustments of the Radiance simulation process are currently allowed in OpenStudio. The different illuminance targets for senior housing and regular housing cannot be demonstrated, and corresponding lighting schedules cannot be generated, so the simulation results would not be accurate. Thus, for this study, a modified process is developed to address this issue.

Figure 2 shows the tools and the process for this simulation methodology. After the regular building energy simulation in OpenStudio, the annual daylight illuminance data from the ill file simulated by Radiance are located, and analyzed in Excel. The average hourly monthly illuminance tables for each space are generated for daylighting condition evaluation and lighting schedule calculation. Figure 3 shows one example of the illuminance table, for a room with the illuminance target of 300 Lux. Each cell shows the average illuminance of a room at one hour in a month. Figure 4 shows the lighting schedule generated for the same room. The lighting schedule of each hour is determined by how much more illuminance is needed to reach the illuminance target and what percentage of the target it accounts for. The hours considered for daylighting are 7:00 to 17:00. If the

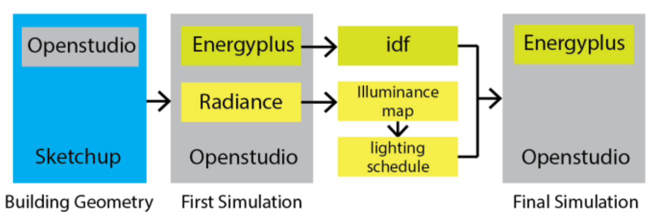


Figure 2. Simulation tools and process

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7:00 | 77 | 90 | 137 | 175 | 206 | 199 | 197 | 179 | 159 | 140 | 117 | 92 |
| 8:00 | 135 | 159 | 202 | 239 | 266 | 265 | 240 | 226 | 217 | 201 | 165 | 145 |
| 9:00 | 179 | 218 | 264 | 290 | 306 | 307 | 297 | 267 | 259 | 229 | 211 | 192 |
| 10:00 | 235 | 276 | 295 | 335 | 376 | 356 | 312 | 297 | 293 | 278 | 253 | 217 |
| 11:00 | 273 | 313 | 353 | 391 | 432 | 399 | 402 | 346 | 365 | 369 | 367 | 302 |
| 12:00 | 355 | 421 | 432 | 468 | 537 | 476 | 504 | 433 | 511 | 594 | 551 | 473 |
| 13:00 | 456 | 544 | 545 | 643 | 796 | 704 | 827 | 858 | 825 | 748 | 657 | 549 |
| 14:00 | 426 | 539 | 586 | 774 | 926 | 877 | 1194 | 1128 | 1064 | 798 | 543 | 440 |
| 15:00 | 260 | 377 | 474 | 591 | 838 | 794 | 1198 | 1108 | 944 | 527 | 286 | 220 |
| 16:00 | 50 | 110 | 196 | 286 | 447 | 480 | 773 | 658 | 372 | 89 | 22 | 16 |
| 17:00 | 0 | 2 | 16 | 39 | 83 | 133 | 185 | 117 | 21 | 0 | 0 | 0 |

Figure 3. Monthly hourly illuminance of one room (Lux)

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7:00 | 74% | 70% | 54% | 42% | 31% | 34% | 34% | 40% | 47% | 53% | 61% | 69% |
| 8:00 | 55% | 47% | 33% | 20% | 11% | 12% | 20% | 25% | 28% | 33% | 45% | 52% |
| 9:00 | 40% | 27% | 12% | 10% | 10% | 10% | 10% | 11% | 14% | 24% | 30% | 36% |
| 10:00 | 22% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 16% | 28% |
| 11:00 | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |
| 12:00 | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |
| 13:00 | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |
| 14:00 | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |
| 15:00 | 13% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 27% |
| 16:00 | 83% | 63% | 35% | 10% | 10% | 10% | 10% | 10% | 10% | 70% | 93% | 95% |
| 17:00 | 100% | 99% | 95% | 87% | 72% | 56% | 38% | 61% | 93% | 100% | 100% | 100% |

Figure 4. Lighting schedule of one room

average illuminance of an hour exceeds the illuminance target, the light will be set to 10% on for a conservative consideration. Then, the new schedules need to be synthesized with the existing lighting schedules and manually input into OpenStudio for the final simulation. The third and fourth models are simulated using this method. The cooling, heating, equipment, lighting, and total energy consumption of the four models are the final results needed.

## IV. SIMULATION

### A. *Simulation Model Introducation*

The simulation model is a senior apartment located in Changsha, south-central China. Changsha is at the longitude 112 °E and the latitude 28 °N. It has a humid, subtropical climate [14]. According to the Köppen-Geiger classification, this climate is the same as that of the southeastern US; thus, the ASHRAE standard for climate zone 4 is used.

This apartment, which has seven floors, is one of the most common types of housing in China. Figure 5 shows the model of the building. This building is an independent living apartment. The first floor is the public area, and the second through seventh floors are the living area. Figure 6 shows the floor plan. There are 28 rooms on each floor, and there are five major types of rooms: west-facing rooms, recessed south-facing rooms, south-facing rooms with balconies, south-facing rooms, and east-facing rooms. In this study, one room of each type is selected for simulation. Table II shows the characteristics of the five rooms. Ideal loads air system is used for simulation.

### B. *First Energy Model*

The first energy model is the baseline model for a regular apartment. It uses the ASHERAE 90.1-2004, midrise apartment, climate zone 4, as the template. To simplify the

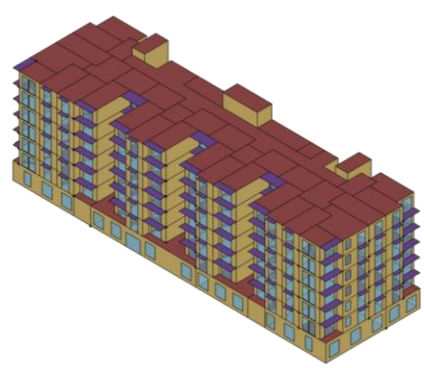

Figure 5. The building model

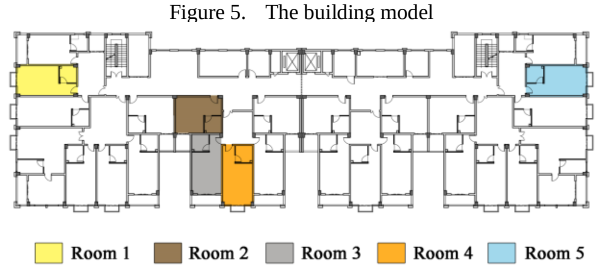


Figure 6. Floor plan and room selection

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TABLE II. CHARACTERISTICS OF ROOMS

| ROOM | Description | Room dimension (width*depth*height) [m] | Area [$m^2$] | People / room | Gross Wall Area [$m^2$] | Window area [$m^2$] | Window to floor ratio | Balcony dimension (Width*depth) [m] |
|---|---|---|---|---|---|---|---|---|
| **1** | West facing | 4.20*8.20*3.25 | 34.44 | 2 | 13.66 | 4.86 | 14.1% | 2.00*0.90 |
| **2** | South facing and recessed | 6.40*5.10*3.25 | 32.64 | 2 | 7.15 | 4.86 | 14.9% | 2.20*2.50 |
| **3** | South facing with balcony | 4.20*8.20*3.25 | 34.44 | 2 | 40.33 | 4.86 | 14.1% | 4.20*1.50 |
| **4** | South facing | 4.20*8.20*3.25 | 34.44 | 2 | 23.42 | 4.86 | 14.1% | 2.00*0.90 |
| **5** | East | 4.20*8.20*3.25 | 34.44 | 2 | 13.66 | 4.86 | 14.1% | 2.00*0.90 |

simulation, only the five rooms are modeled in detail, and each of the five rooms is assigned to an individual thermal zone.

### *C. Second Energy Model*

The second energy model is the adjusted baseline model used to demonstrate the energy consumption of senior housing. To meet the special lighting and thermal levels for seniors' comfort and health, the lighting power density and temperature setpoint are adjusted. To represent a more accurate living pattern and the occupation status of seniors, the schedules are changed accordingly.

*1) Lighting power density:*

As stated earlier in the literature review, the lighting power density is changed from 3.88 W/$m^2$ (0.36 W/$ft^2$) to 10.76 W/$m^2$ (1 W/$ft^2$) to meet the lighting level for seniors' visual comfort.

*2) Temperature setpoint:*

The heating temperature setpoint is changed from 21.1 °C (70.0 °F) to 22.2 °C (72.0 °F). The cooling temperature setpoint is changed from 23.9 °C (75.0 °F) to 25.0 (77.0 °F).

*3) Schedule:*

As distinct from regular residential buildings, senior living buildings are occupied more hours of the day, sometimes even 24 hours a day. In this study, data from the American Time Use Survey (ATUS) [15] are used to determine the daily activity of the elderly, and the average lighting, equipment, and occupancy schedules are generated. In future studies, more accurate schedules for the seniors in China need to be developed. In normal mid-rise apartments during the day, the lighting and occupancy schedule can be as low as 10% to 30% occupied, and the equipment schedule can be about 60% to 70% on. For this study, the lighting and equipment schedules for senior housing are changed to 100% on during the day. The occupancy schedule is changed to 80% to 90% occupied during the day.

### *D. Daylighting Simulation*

For the daylighting simulation, using the OpenStudio plug-in in SketchUp, 5×5 illumination maps of 25 sensor points are placed into the five rooms, and the daylighting controls are placed in the center of the rooms. They are all at the height of 762 mm (2.5 ft). Simple glazing system windows is used in the model. The U-factor of the window is 2.95 W/$m^2$·K (0.52 Btu/$ft^2$·h·R). The Solar Heat Gain Coefficient is 0.39. The visible transmittance is 0.27. The annual daylight illuminance data are simulated so that they could be used for the lighting schedule and daylighting condition analysis. Because the building geometry and material data are the same for the third and fourth model, the daylighting simulation results are applied to both of them.

### *E. Third Energy Model*

The third model is the regular apartment with daylighting. The building geometry and all the building data, except the lighting schedule, are the same as for the first model. 75 Lux (7.5 FC) is used as the target illuminance, and lighting schedules are generated using the data from daylighting simulation.

### *F. Fourth Energy Model*

The fourth model is the senior apartment with daylighting. Lighting schedules are generated based on the target of 300 Lux (30 FC). All the other model data are the same as for the second energy model.

## V. RESULTS AND ANALYSIS

### *A. Daylighting Simulation Results*

Figure 7 shows the annual average illuminance and average peak illuminance of the five rooms. The red line is the average illuminance target for senior housing, which is 300 Lux (30 FC), as required by IES. The yellow line is the average illuminance target for regular housing. An optimal design should have the average illuminance above the goal without high peak illuminance.

The glazing material has a visible transmittance of only 0.27, which is low for daylighting purpose. Therefore, the average illuminance for all the rooms is acceptable for normal housing, but insufficient for senior housing. The south room without balcony has the highest average illuminance, and the west room has the highest peak illuminance.

In Figure 8, the blue line shows the percentage of time that a room's illuminance reaches the target of 300 Lux. The red line shows the percentage of time the room illuminance exceeds double the target, in which case the light might cause too much heat gain or a glare, and the occupants might close the window blind. The green line shows the percentage of time that the room illuminance is between 300 and 600 Lux, which is the appropriate level of light for seniors. The lighting conditions for all the rooms need improvement because more than half of the time the illuminance cannot reach the target. The daylighting performance of the recessed

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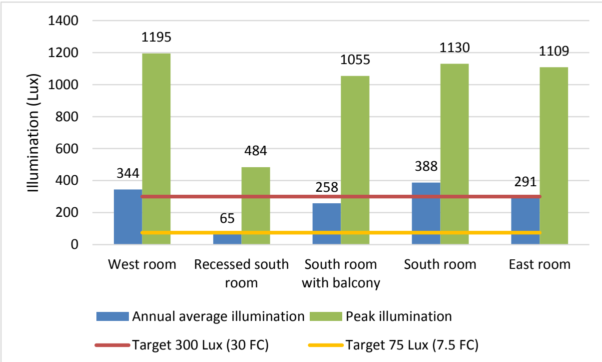


Figure 7. Annual average illuminance of 5 rooms

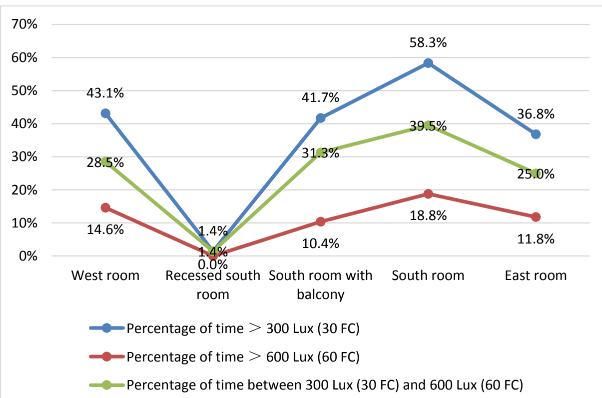


Figure 8. Percentage of time reaching target

south room is far from ideal, and this type of room should be avoided in senior housing design. The other four room types all have the potential for improvement.

Daylighting conditions of this apartment could be improved through design decisions such as adjusting the size and position of windows, increasing the transmittance of glazing material, changing the reflectance of interior material, and adding proper shading devices.

## B. *Energy Simulation Results*

Figure 9 shows the energy simulation results of the four models. The blue dots are the total EUI, and the clustered columns show the EUI breakdown. Figure 9 (a) shows the EUI of the baseline model for regular housing. Of the five selected rooms, the recessed south room has the lowest total EUI, and the south room with balcony has the highest EUI. These results are explained by the fact that these two rooms have the least and greatest exterior wall area. Cooling energy is the largest component of energy consumption. Equipment energy is the second largest, and lighting and heating energy only account for a small proportion of total energy.

Figure 9 (b) shows the EUI of baseline model for senior housing. Compared to the first energy model, the average EUI increases 2.33 times, which matches the previous findings [5]. The south room has the highest EUI, but the total EUI difference among the five rooms is not obvious. The lighting energy increases 5.40 times, and the cooling energy increases 2.57 times. Even though the temperature setpoint for senior housing is higher, the cooling energy is even larger, and the heating energy is even smaller. The main reasons for this result are the extra heat gain from the increased lighting and the greater number of occupied hours.

Figure 9 (c) shows the EUI of the regular housing with daylighting. The average energy saving is 1.07%. The average lighting energy saving is 6.57%, and the average cooling energy saving is 0.98%. Because the rooms are not occupied for most of the daylighting hours, the lighting energy saving is not obvious. There is a slight decrease in cooling energy and increase in heating energy because of the lower amount of heat generated by the lower level of electrical lighting.

Figure 9 (d) shows the EUI of the senior housing with daylighting. The average energy saving is 16.75%. The average lighting energy saving is 32.39%, and the average cooling energy saving is 14.16%. Even without any design improvements, there is significant decrease in lighting and cooling energy compared to the energy savings in regular apartment. Therefore, daylighting is a more efficient energy savings method for senior housing. Design optimizations will be experimented in future studies to further improve the energy performance. Temperature settings can also influence the energy consumption greatly. Due to the high cooling energy and low heating energy in senior housing, higher temperature setpoints could be considered so long as a comfortable thermal environment is maintained. The EUI of the recessed south room is much higher than the other four rooms, due to its limited access to daylight.

# VI. CONCLUSION

This paper presented an approach for modeling the energy performance of senior housing and the energy savings through daylighting.

The energy consumption of senior housing is more than two times higher than that of normal housing, and the energy increase is mostly from cooling and lighting energy. Daylighting is a suitable energy savings strategy for senior housing. The natural light in the case study building is inadequate and the daylighting condition needs to be optimized, but the energy saving is obvious even in current condition. Daylighting can reduce the building’s lighting and cooling energy, and it works more effectively for senior housing than for regular residential buildings.

The energy performance of the five rooms in this building varied greatly when simulated as regular housing or senior housing. These results indicate that senior housing should be specially designed to achieve the optimal energy and daylighting performance.

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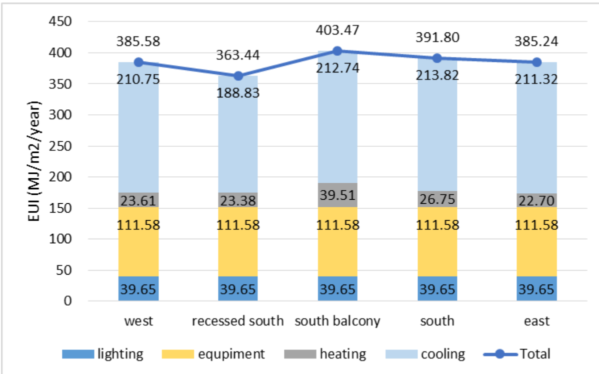
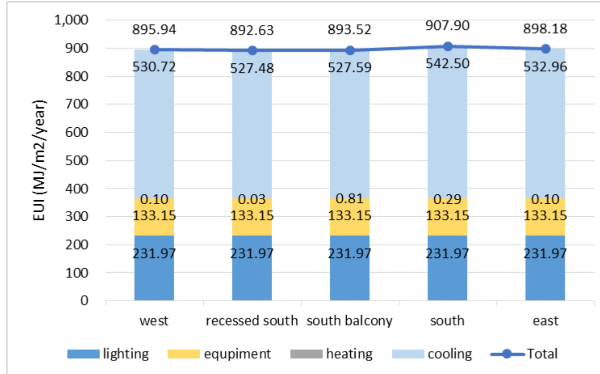
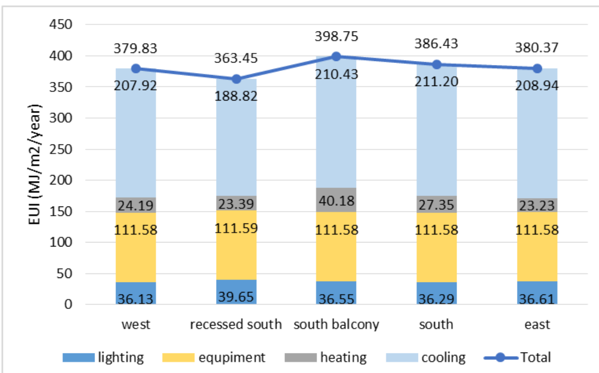


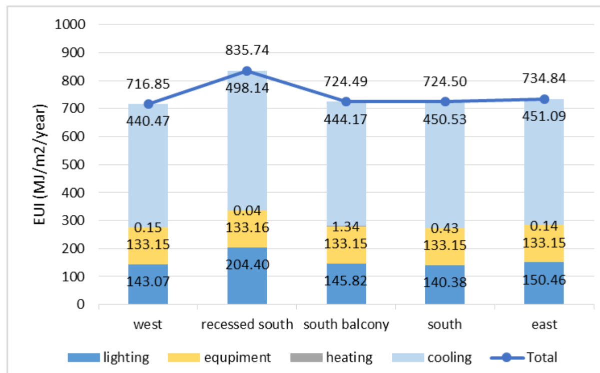

(a) EUI of the first model




(b) EUI of the second model




(c) EUI of the third model




(d) EUI of the fourth model

Figure 9. EUI of the four models

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