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SENSITIVITY ANALYSIS OF SKYLIGHT AND CLERESTORY DESIGN ON ENERGY AND DAYLIGHT PERFORMANCE OF A RETAIL BUILDING

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ABSTRACT

Daylight and energy performance are essential for sustainable building design. Skylights and clerestories are effective strategies for providing sufficient daylight while reducing building energy requirement. To identify the most influential variables of the skylight and clerestory design, a parametric design model of a retail building is developed and 1000 design options are randomly selected. Integrated daylight and energy simulations are performed for each option to evaluate the lighting and thermal loads simultaneously. The performance indices for daylighting and energy performance evaluation are Useful Daylight Illuminance (UDI) and Energy Use Intensity (EUI). Then, a sensitivity analysis is used to rank building design variables according to their contribution to the variance of UDI and EUI. The design features of the optimal and worst design options are also discussed.

INTRODUCTION

Daylight is a key component in sustainable building design because of its influence on occupant comfort, health, and building energy efficiency. This study focuses on the design of skylights and clerestories of a retail building. The purpose is to identify the best and worst design options and design variables' influence on daylight and energy performance.

Artificial light and natural light usually work together to provide lighting in modern buildings. Natural light is an essential part of the lighting system, because negative effects on occupants' health were found if artificial lighting is the only light source (Stevens, 2001; Basso Jr, 2001). Natural light can help to maintain occupants' health, improve mood, reduce fatigue, and reduce eyestrain (Edwards & Torcellini, 2002). Full-spectrum light from the sun is the best source of light for human eyes, however, most artificial light is only concentrated in a certain portion of the spectrum, which may lead to eye functioning problems (Edwards & Torcellini, 2002). The wavelength of light also influences many other health issues, such as nervous system, circadian rhythms, and endocrine system problems (Edwards & Torcellini, 2002).

The advantages of daylighting designs in different building types have been documented in various studies. Specifically, it is found that proper daylight design in retail buildings can increase sales (Heschong et al., 2002), improve customer satisfaction, and promote productivity (Boyce et al., 2003). Skylight is an effective lighting and energy saving method, however, it is still not widely applied in the industry. Only approximately 2–5% of commercial building floor space has sufficient skylight area (Lawrence & Roth, 2008). Therefore, it is necessary to advise designers and practitioners on how skylight strategies impact the building's energy loads and what is the most energy efficient design solutions.

The calculation of energy savings from daylight system is a complex process. Daylight system can provide daylight illumination which results in a reduction in lighting and cooling loads; it can also transmit solar radiation and heat which results in an increase in cooling loads and reduction in heating loads. Therefore, an integrative approach is needed to calculate the various influence of daylight system simultaneously.

Parametric design in architecture refers to the modeling process of building geometry using parameters and functions. The advantage of parametric design over traditional design method is its ability to quickly generate design alternatives. Parametric design maintains dynamic links between parameters and geometry defined by the parameters. The modification of parametric values leads to simultaneous updates of the building geometry. Once a parametric building model is developed, design alternatives can be rapidly generated through the manipulation of parameters. Furthermore, when parametric design is coupled with building performance simulation, building performance data of each design alternative can be obtained and utilized to analyze their relationships.

Sensitivity analysis is a valuable tool for building performance analysis. Sensitivity analysis has been widely used to explore the building performance in various types of applications, such as building design, calibration of energy models, building retrofit, and impact of climate change on buildings (Tian, 2013). Based on the simulation data, sensitivity analysis is used to identify and prioritize the most influencing design variables.

The objective of this study is to develop a simulation framework which integrates parametric design, daylight simulation, and energy simulation, and to analyze the relationship between design variables and building performance metrics. The research framework is applied to the skylight and clerestory design of a retail building. The results indicate which design variables are the most significant considering the daylighting and energy performance. In addition, the optimal and worst design options of the case study building could provide references for designers and practitioners.

SIMULATION

Simulation framework

Figure 1 shows the research framework of this paper. The research process begins with developing parametric building geometry with 8 design variables. The parametric model is developed using Rhino and Grasshopper. Grasshopper plug-ins Ladybug and Honeybee are used for energy and daylighting modeling, and the simulation process is executed in EnergyPlus and Radiance. An integrated daylighting and energy simulation method is constructed to examine the heating, cooling, and lighting loads simultaneously. A daylighting simulation runs first to calculate the illuminance at the lighting sensor positions for every hour in a year. A certain percentage of artificial light is turned off or dimmed depending on the daylight availability. A year-long lighting schedule is generated and import into energy model for the energy simulation.

The solution space for the design is represented by a sample of 1000 design options. The sample is randomly selected from all the possible combinations of all the design variables. A Grasshopper plug-in, Octopus is used as an engine to generate the 1000 design option and automate the 1000 daylight-energy simulation process. The performance metrics obtained from the simulation are Energy Use Intensity (EUI) and Useful Daylight Illuminance (UDI). Explanations of the performance metrics will be discussed in the simulation output section. Finally, based on the building variables data and simulation result, sensitivity analysis is performed to identify and prioritize the most influencing design variables.

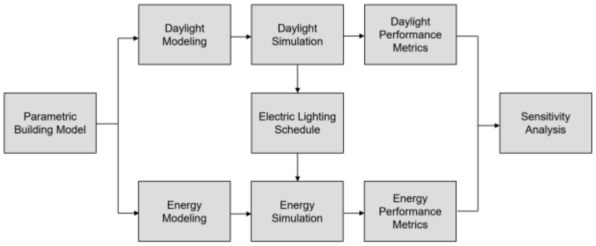


Figure 1 Integrated daylight and energy simulation

Building variables

A single-story retail building located in Atlanta, Georgia is used as the case study building (Figure 2). The area of the building is 2000 square meters, which is the typical size of a small supermarket. The building has a flat roof that is 6 meters high. Daylight in the building is provided by both skylights and clerestories. The skylights are curb mount skylights, which means the glazing is raised from the roof plane. The footprint of each skylight is a square shape, while the glazing is a rectangular shape with various length. The curb height on the south and north vary independently, thus the glazing can face the north or south of the sky. The skylights are laid out on a grid on the roof. The number of skylights varies from 42 to 50 depending on the shape of the building. The size of each skylight varies from 0.25 to 2.25 square meters, which is the typical size of a skylight component. Considering the skylight number and the skylight dimension, the skylight to floor ratio varies from 0.5% to 5%. There are clerestories on the four facades of the building. The width of the skylight is same as the length of the facade, while the heights of the clerestories vary. The top border of the clerestory is fixed on the top of the façade, so the height of the clerestory depends on the location of the bottom border.

The 8 design variables define the shape, height, size, placement of the skylights, the size of clerestories, and the shape of the building. The combination of these variables is not found in precedent skylight studies. The design variables are marked in Figure 2 and Figure 3. Figure 3 is the enlargement of the southeast corner of the building. The design variables include building depth, the distance between the skylight and the roof perimeter, the length of the side of the skylight, the south curb height, the north curb height, the height of south clerestory, the height of north clerestory, and the height of east and west clerestory. The ranges of the variables are explained in Table 1. The 8 variables are named V1 to V8 for short. The range of each variable is divided into 10 steps for the simulation. Each variable can vary independently, and take any value at the 10 steps.

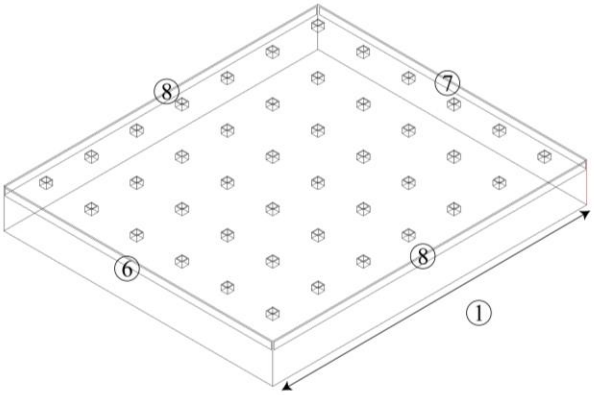


Figure 2 Building geometry and variables

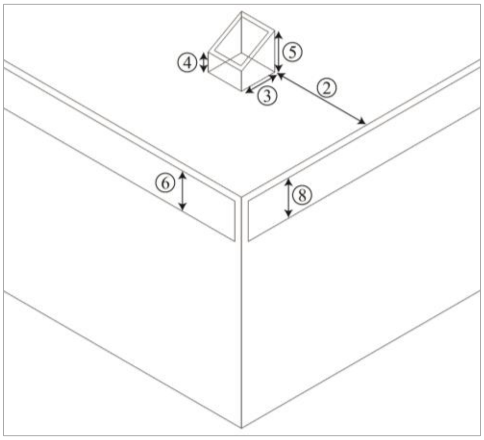


Figure 3 Skylight geometry and variables

Table 1 Design variables

	VARIABLE	SHORT NAME	RANGE	
			MIN [M]	MAX [M]
1	Building depth	V1	30.0	66.7
2	Distance between skylight and roof perimeter	V2	0.5	5.0
3	Length of the skylight	V3	0.5	1.5
4	South curb height	V4	0.1	1.5
5	North curb height	V5	0.1	1.5
6	Height of south clerestory	V6	0.1	2.0
7	Height of north clerestory	V7	0.1	2.0
8	Height of east and west clerestory	V8	0.1	2.0

Daylight and energy modeling

After the parametric building geometry is built, Ladybug and Honeybee are used for daylight and energy modeling. The daylight and energy models are built with DOE commercial reference buildings template.

In the daylighting modeling process, there are about 45 daylighting sensors spaced on a grid on the height of 0.76 meters above the floor. As the shape of the building changes, the number of the sensors might be different. The parametric building geometry is connected to Radiance materials component, with the setting of material transparency, reflectance, etc. Typical interior finishes are used for the daylight simulation. The reflectance of the ceiling, floor, interior, and exterior walls are respectively 0.8, 0.2, 0.5, and 0.5. The clerestory glazing material is a typical clear glazing material with visible transmittance of 0.65. The skylight glazing material is an insulated translucent material to avoid excessive heat gain and direct sunlight. It has a low transmittance of 0.24. Then the building materials are connected to daylighting simulation component, with the input of weather files, daylighting sensors, and other simulation settings. A rad file is generated and daylighting simulation is executed in Radiance. After simulation, Ladybug imports simulation result file back to Grasshopper, reads the daylight performance metrics, and generates an annual lighting schedule.

In the energy modeling process, the parametric building geometry is connected to EnergyPlus building materials, and connected to a Honeybee thermal zone component. Honeybee assigns construction set, schedules and internal loads for the space based on the building type and climate zone. This model uses supermarket construction set, loads, schedules, and thermostat settings. The building construction materials for the models is DOE Ref 2004 supermarket, Climate Zone 3. One material that is not from the template is the insulated translucent skylight material. The U-Value of the material is 0.45, which is much lower than regular glazing materials. The lighting schedule generated by daylighting simulation is also added to the energy model. An idf file is generated and energy simulation is executed in EnergyPlus. Ladybug brings the energy simulation result back to Grasshopper and reads the energy performance metrics.

Simulation output

The daylight performance metric is Useful daylight illuminance (UDI). UDI is the ratio of the number of hours in the year when illuminance provided by daylighting is within a useful range, to the total number of occupied hours in a year (Nabil & Mardaljevic, 2005). UDI aims to determine the daylighting level that is neither too dark nor too bright (Reinhart, Mardaljevic, &

Rogers, 2006). UDI is usually presented by three metrics: UDI <100 lux, UDI 100-2000 lux, and UDI >2000 lux. The illuminance range that considered useful is between 100 lux to 2000 lux. Illuminance below 100 lux is considered as too dark, and illuminance above 2000 lux is considered too bright.

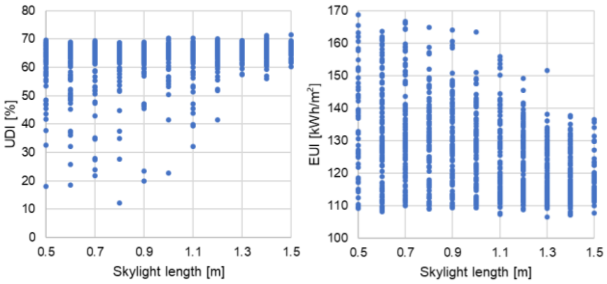
The energy simulation output includes annual heating, cooling, equipment, and lighting energy loads. Energy performance metric is EUI (Energy Use Intensity). EUI is calculated by dividing the total energy load (the sum of heating, cooling, and lighting loads) by the floor area.

A higher UDI value is preferred, as it indicates more useful daylight illuminance. A lower EUI value is preferred, as it indicates lower energy demand by the building. These two performance indices work together to find design options with high daylight availability and low energy requirement.

DISCUSSION AND RESULT ANALYSIS

Scatterplot

The first type of scatterplot plots one design variable against one performance metric to show their relationship. Scatterplots can usually show which variable is having a strong impact on the outputs. Variables with a significant impact show a clear trend, while variables with a low impact do not show any trend. As an example, Figure 4 (1) and (2) graphically present the effect of the length of the skylight on UDI and EUI, and a clear trend can be found in both figures. UDI increases with the increase in skylight length, while EUI decreases with the increase in skylight length. Since a high UDI and a low DUI is preferred for a design option, it seems that a larger skylight length is likely to contribute to a good design. However, it is still impossible to make conclusions on what is the best variable value and the exact influence and importance of design variables. Therefore, other types of scatterplot and sensitivity analysis method is required.

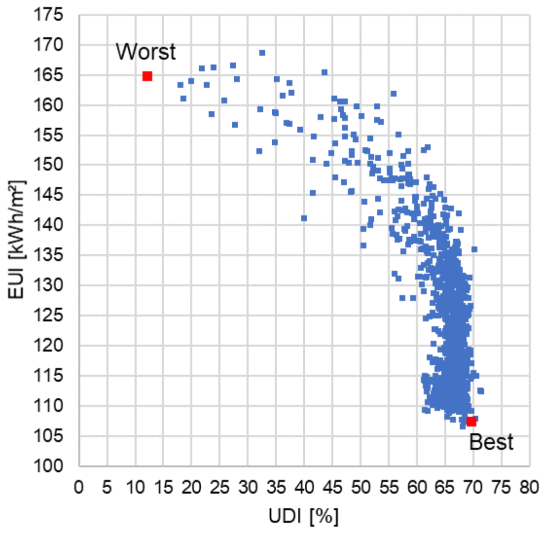


(a) (b)

Figure 4 Scatterplots of UDI and EUI against skylight length

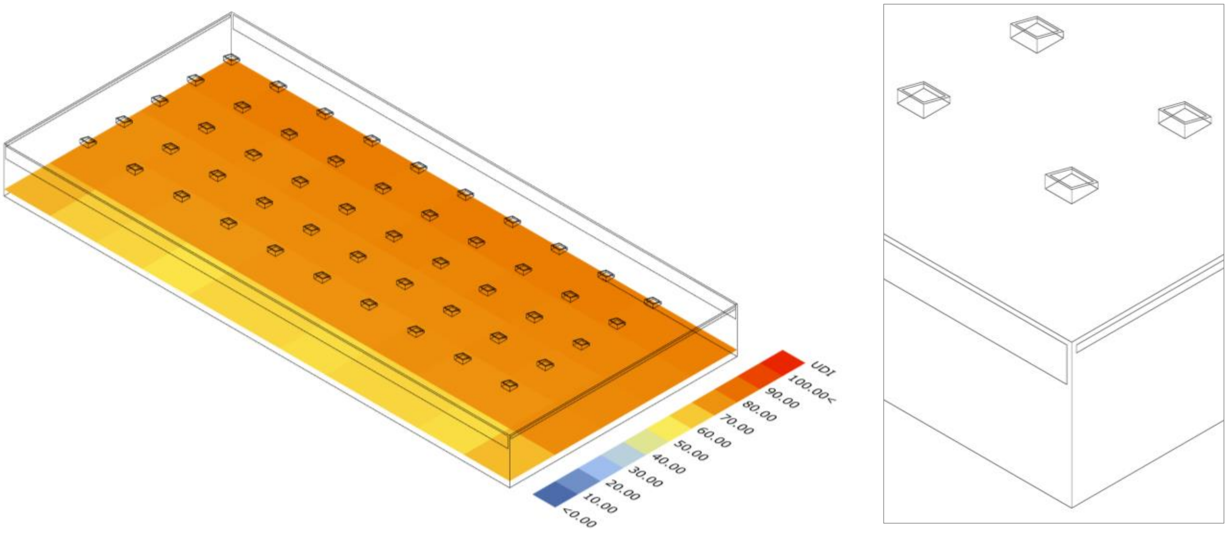
The second type of scatterplot is the plot of the daylight against energy performance indices for the 1000 design options (Figure 5). It can be observed that the UDI and EUI values are negatively correlated. It means that good designs tend to perform well in in both daylight and energy metrics, and bad designs tend to perform poorly in both metrics. Most data points are clustered at the bottom right of the graph, where the UDI is between 60 and 70, and EUI is between 105 and 145 kWh/m^2. It means that good daylight performance is relatively easy to achieve, and many data points have high UDI value, but only a few of them have good energy performance at the same time. The shape of the plot resembles a mirrored exponential distribution, which is worth further exploration.

The best and worst options at the opposite side of the graph are marked with red color in the plot. It needs to be noticed that they are not the absolute best and worst design options, but two cases selected from in the 1000 options that have relatively good or bad performance considering the two performance metrics. The value of the 8 design variables and the performance indices of the best and worst design option are listed in Table 2. Their geometry and UDI simulation result are shown in Figure 6 (a) and Figure 7 (a). The southeast corner of the building is zoomed in to show the skylight geometry more clearly in Figure 6 (b) and Figure 7 (b). The UDI of the best design is 5.7 times higher than the worst design option, and the EUI of the best design is 34.6 % lower than the worst design option.



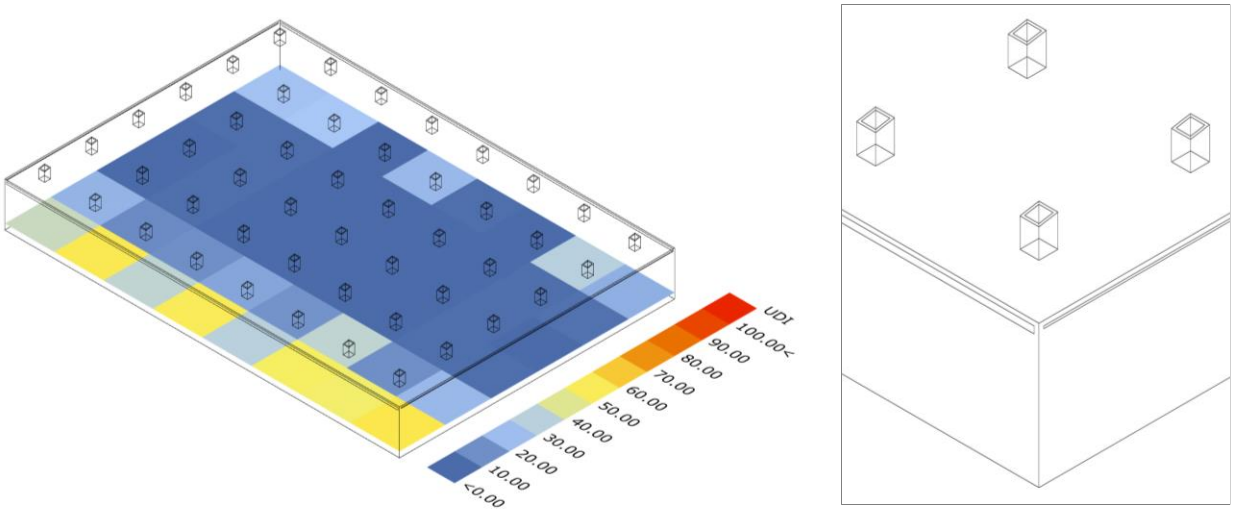
(a) EUI against UDI

Figure 5 Scatterplots of 1000 design options



(a) Building geometry (b) Skylight geometry

Figure 6 Best design option



(a) Building geometry (b) Skylight geometry

Figure 7 Worst design option

The majority of daylight sensors in best design option have UDI of 70 to 80. Only the sensors near the south facade has UDI of 50 to 60. The design has a small building depth and a wide facade. The skylights are 5 meters from the roof edge, which is the highest value possible. The daylight provided by clerestories could be the reason that the skylight does not need to be placed near the roof perimeter. This indicates a distance larger than 5 meters could be the optimal value, and a wider range of values needs to be considered in future studies. Also, different distances from the south, north, east, and west perimeter could also be explored, since in the best design option, the height of clerestories differs for the four facades. The length of the skylight is 1.0 m, which makes the skylight to floor ratio 3%. Motamedi and Liedl (2017) suggested skylight ratios of 3% - 14% for energy efficiency. This result is consistent with their finding. The curb height is 0.52 m on the south and 0.24 m on the north, so skylight is slightly facing north, which could help reduce direct solar radiation. The design has large clerestories on the south and north (1.43 m and 1.62 m high), and small clerestories on the east and west (0.29

m high). This is also consistent with sustainable design rule of thumbs.

UDI of the worst design option is about 10 to 20 at most sensor locations. The building shape of the worst design option is deeper and the facade is narrower than the best design option. The problem with worst design option is mainly the insufficiency of daylight. Almost all variable values, including the size of skylight, size of clerestory, and height of curb lead to a minimum daylight availability. As a result, the lighting and cooling energy loads are significantly increased compared to other design options.

Table 2 Design variable values and performance indices of best and worst design options

	VARIABLE	**BEST OPTION [M]**	**WORST OPTION [M]**
1	Building depth	30.00	37.33
2	Distance between skylight and roof perimeter	5.00	2.30
3	Length of the skylight	1.10	0.80
4	South curb height	0.52	1.22
5	North curb height	0.24	1.36
6	Height of south clerestory	1.43	0.29
7	Height of north clerestory	1.62	0.29
8	Height of east and west clerestory	0.29	0.10
PERFORMANCE INDICES		**BEST OPTION**	**WORST OPTION**
UDI [%]		70.30	12.30
EUI [kWh/m^2]		107.80	164.80

Sensitivity analysis

The sensitivity analysis is performed to determine the contribution of each input variable to the variance of the building performance outputs. Statistical analysis software R and the package 'sensitivity' (Pujol et al., 2017) is used to perform the sensitivity analysis. This package includes numerous sensitivity analysis methods. Regression method is the most widely used method for sensitivity analysis in building energy analysis (Tian, 2013). This is because this method is fast to compute and easy to understand. The sensitivity analysis indicator for this study is SRC (Standardised Regression Coefficients). The sensitivity index SRC has been widely used in building energy analysis.

A larger absolute value of SRC indicates a larger impact on the performance index. Table 3 and Table 4 rank the importance of design variables on the daylight and energy performance by the absolute value of SRC.

Table 3 Variables ranked by influence on UDI

RANK	**VARIABLE**	**SHORT NAME**	**SRC**
1	Height of east and west clerestory	V8	0.39
2	Length of the skylight	V3	0.29
3	Height of north clerestory	V7	0.27
4	Height of south clerestory	V6	0.11
5	South curb height	V4	-0.10
6	Building depth	V1	-0.06
7	Distance between skylight and roof perimeter	V2	0.05
8	North curb height	V5	-0.04

Table 4 Variables ranked by influence on EUI

RANK	**VARIABLE**	**SHORT NAME**	**SRC**
1	Height of east and west clerestory	V8	-0.56
2	Length of the skylight	V3	-0.43
3	Height of south clerestory	V6	-0.24
4	South curb height	V4	0.21
5	Height of north clerestory	V7	-0.20
6	Building depth	V1	-0.11
7	North curb height	V5	0.09
8	Distance between skylight and roof perimeter	V2	-0.08

The top two most influencing variables for both daylight and energy performance are the same, namely the height of east and west clerestories, and the length of skylight. The three variables related to clerestories are all ranked top 5 for both daylight and energy performance. One major reason for the high ranking is the choice of glazing materials. In the energy model, the glazing material for clerestories is regular clear glass, and the material for skylight is an insulated translucent material. Therefore, both energy and daylight performance indices are more sensitive to the change in clerestory height because of the higher U-value and higher transmittance of the clear glass. It would be interesting to test how the rank differs if the same material for skylights and clerestories are used in a future study. The height of east and west clerestory is ranked the first because it controls clerestories on two facades. It is reasonable that it could cause more variation in performance indices than the north or south clerestory alone.

The high ranking of the length of skylight is also reasonable, because it directly controls the size of the skylight and how much daylight and solar radiation is admitted into the building. South curb height is more important than the north curb height is because the south curb blocks the direct sunlight from the south, while the north curb only blocks diffused daylight. The building depth, north curb height, and the distance between skylight and roof perimeter are the variables with the lowest rankings. Glazing is the most sensitive part of the building, because of the low insulation level and the admission of sunlight, but these variables are not directly related to it. Undoubtedly, their influence on the daylight and energy performance are subtle and difficult to detect when compared to glazing related variables. However, the influence of these variables should not be neglected because they show a great difference in the best and worst design options. To avoid this problem, in future studies, the effect of these variables could be tested separately when the glazing size is fixed.

A positive SRC indicates a positive effect on the performance index, and a negative SRC indicates a negative effect. It means that an increase in this variable result in the increase in UDI and decrease in EUI, and vice versa. Since a high UDI and low EUI is desired, a change in this variable could improve and impair daylight and energy performance at the same time. The only variable that has the different effect on daylight and energy performance is building depth. Increase in building depth would decrease daylight performance while improve energy performance.

The influence of sample size on linear regression models for daylight and energy is also explored. Sensitivity analysis is performed using samples of 200, 400, 600, 800, and 1000 observations. SRC is calculated for each sample. Figure 8 (a) and (b) show the variation of SRC for UDI and EUI over the different samples. It can be clearly seen that SRCs are stabilized by an increasing sample size. Sample size seems to have a larger influence on the SRCs for UDI. Some SRC values calculated from small sample sizes are 2 to 3 times larger than the ones calculated from the larger sample sizes, which makes the ranks of variables also considerably different for different sample sizes. The SRC values for EUI obtained from various sample sizes seem to be more stable, but SRCs from sample size of 200 still show great difference from the ones from other sample sizes.

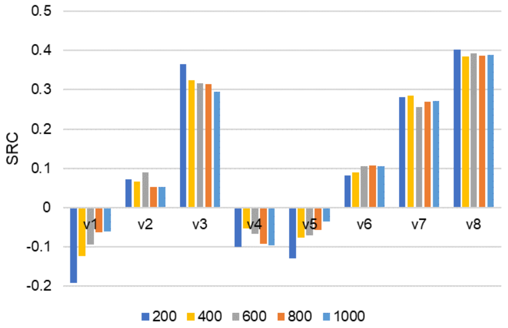
CONCLUSION

This study focuses on the skylight and clerestory design of a retail building. A simulation framework which integrates parametric design, daylight simulation, and energy simulation is developed using Grasshopper, Ladybug, and Honeybee. 1000 building design options are randomly selected and two performance indices (i.e. UDI and EUI) are obtained from daylight and energy simulation.

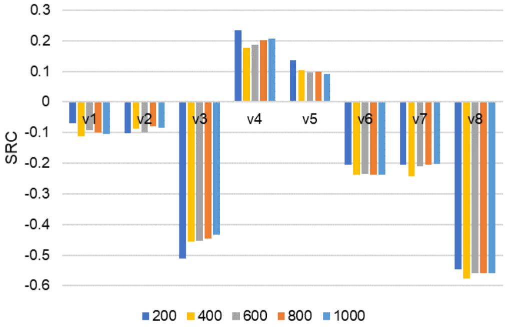
Scatterplots are developed to graphically show the relationship between design variables and performance metrics, the relationship between daylight and energy performance, and identify best and worst design options. The best design option has a skylight ratio of 3%, skylight far from the roof perimeter, small building depth, low curb height, large clerestories on the north and south, and small clerestories on the east and the west.

Sensitivity analysis is performed to quantitatively evaluate the impact of design variables on daylight and energy performance metrics, and the sensitivity analysis indicator SRC is calculated. Results show that the height of east and west clerestories and dimension of skylight are the most influencing variables for both daylight and energy performance.

It should be noticed that these results are valid for this specific building design and location. Future studies are needed for different locations, different design alternatives, different range of design variables, and different materials, so that more solid design suggestions can be provided.



(a) SRC for design variables and UDI



(b) SRC for design variables and EUI

Figure 8 Standardized regression coefficients for different number of observations

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