The Impact of Ceiling Geometry and its Sensitivity on Daylighting and Energy Performance of Skylights

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Abstract. This study aimed at the assessment of the actual building ceiling depth on the predictions of skylight performance. Using the integrated Radiance and EnergyPlus simulation tools, daylighting and energy performance of skylight to roof ratios from 1% to 25% with a ceiling depth of 1.5 m to 3 m were assessed and analyzed. The results showed that including the ceiling depth into simulation model greatly affected the predictions of the skylight performance. Through a sensitivity analysis, the study indicated that the impact of ceiling geometry increased as the skylight’s contribution to the reduction of building energy consumption increased with 6% skylight to roof ratio being the most sensitive to the ceiling depth. The integrated daylighting and building energy optimization concluded that 8%, 9%, 10% and 11% skylight to roof ratios were optimal for a ceiling depth of 1.5 m, 2 m, 2.5 m and 3 m, respectively. The results induced that for skylight related investigations, building ceiling geometry should be included in the simulation models as it plays a crucial role in the actual performance of skylights.

1. Introduction

Approximately, 36% of global final energy is consumed by building sector and lighting is among the biggest building energy consumers. Building artificial lighting consumes around 5–15% of the total building energy consumption [1]. Studies have reported that daylight, if adequately used, can reduce the total building energy consumption up to 20–40% [2]. Therefore, the promotion of natural light, especially for commercial and public buildings, has been one of the effective strategies included in building energy reduction act by different nations. Like other daylighting systems, top–lighting has been extensively studied and its potential in the reduction of building energy consumption and the provision of homogenous illuminance distribution have been proven. The system is generally used to bring natural light into a space lacking facades or deep area where natural light from side openings cannot reach in a useful amount. Moreover, a study has reported that with the today’s urbanization rate, the usefulness of top-lighting system is expected to raise [3].

Previous studies have evaluated the energy and daylighting performance of top–lighting system mostly through the use of various computer simulation programs and one investigation on the energy efficiency of skylight has reported that from 3% to 14% skylight to ceiling ratio, the building energy demand can be reduced by 19% [4]. However, the findings held in the literature regarding the skylight performance can be arguable as the simulation models used in those investigations did not include the vertical geometry of the ceiling. In the view of the fact that skylights are accommodated in a deep layering scheme containing various building functioning systems, such as building structure, air–handling, electric lighting and hung–ceiling layer, their benefits could be less than the findings due to this context in which they are installed.
Therefore, the objective of this study was to parametrically analyze how the actual ceiling depth can alter the predictions on the energy and daylighting performance of horizontal skylight and how this impact varies according to the size of skylight (skylight to roof ratio: SRR). The evaluation done in this study was based on energy efficient skylight and sufficient but yet glare free daylighting design.

2. Research methods
The current study was carried out in four steps. During the first step, the skylight energy efficiency was evaluated through simulation models with the ceiling depth excluded and from the simulation predictions, energy efficient SRRs were defined. In the second step, the pre-defined energy efficient SRRs were re-modeled with the ceiling depth included in the simulation models and their energy efficiency was assessed. For the third step, the variation of the sensitivity of the ceiling depth impact on the skylight performance was evaluated using regression coefficient through a statistical analysis software R. Finally, the study evaluated the skylight daylighting performance according to the ceiling depth.

2.1. Research variables
The size of skylight is the first and foremost factor influencing the energy and daylighting performance of skylight. Hence, SRR (skylight to roof ratio) was one of independent variables considered in this study. As the aim of this study was to evaluate the impact of ceiling depth on skylight performance, the actual vertical dimension of a building ceiling was used as the second independent variable in this study. Depending on the building size, type and equipment to be hosted in the ceiling, a building ceiling can be as deep as 1.52m to 2.74m [5]. Therefore, a ceiling depth of 1.5m to 3m was analyzed in this study and Figure 1 shows the typical ceiling layering scheme and the study variables.

A simulation model with dimensions of 9mX9mX4.5m, representing a small scale of a vast open space of a single-story building or a top floor of a multi-storey building, was modeled and analyzed. The model had a horizontal skylight and no side opening was included for the predictions to be merely related to skylight performance. The thermal and optical properties of the skylight glazing material were 1.98 W/m²K, 0.37 and 0.67 for U-value, shading coefficient and visible transmittance, respectively. This particular glazing type was selected following a previous study that reported its energy efficiency when used for horizontal skylight in five different climatic conditions [6]. The model thermal properties were selected according to Korean Energy-Saving Design Criteria for office and commercial buildings [7]. The U-value for the floor, walls and ceiling were 0.513 W/m²K, 0.429 W/m²K and 0.192 W/m²K, respectively. The reflectance values used for the floor, walls and ceiling were 30%, 50%, and 70%, respectively. All the model thermal and optical properties were kept the same for all the simulation models and are summarized in Table 1.

| Surface | Thermal properties | Optical properties |
|---------|-------------------|--------------------|
|         | U-value [W/m²K]   | Reflectance [%]    | Visible transmittance | Shading coefficient |
| Floor   | 0.513             | 0.3                | –                  | –                  |
| Walls   | 0.429             | 0.5                | –                  | –                  |
| Ceiling | 0.192             | 0.7                | –                  | –                  |
| Skylight| 1.98              | –                  | 0.67               | 0.37               |

2.2. Energy and daylighting modeling tools and conditions
Initially, simulation models were modeled in SketchUp plugin and were then exported to OpenStudio program. To avoid isolated daylighting and energy simulations which could lead to inaccurate predictions, simulations in this study were carried out using OpenStudio’s integrated Radiance and
EnergyPlus simulation programs for daylighting and building energy simulation, respectively. The simulation models contained an illuminance map of 81 measurement points and one sensor point (Figure 2) used for daylighting qualitative analysis and lighting control system, respectively. The 81 measurement points were calculated based on adequate illuminance map layout (0.5 m between wall and contour points and 1 m between two consecutive points) [8]. The location of the sensor point was selected to ensure sufficient lighting at all the occupiable space in the model. A continuous dimming control with three steps was used to control 100% of the artificial lighting of the space. IES (Illuminating Engineering Society) recommendation of adequate lighting for general space (300 lux) was used as illuminance set point.

For the energy simulation, the IWEC (International Weather for Energy Calculation) weather data for Ulsan, South Korea, was used. This type of weather data used has been approved by ASHRAE (American Society of Heating Refrigerating and Air-conditioning Engineers) to represent the typical long-term weather patterns of a given location [9]. The internal loads from people and artificial lighting were included in the model which was treated as a single thermal zone. Lighting power

| Category          | Input               | Values         |
|-------------------|---------------------|----------------|
| Set points        | lighting            | 300 lux        |
|                   | cooling             | 24°C           |
|                   | heating             | 20°C           |
|                   | lighting density    | 11.34 W/m²     |
| Internal loads    | occupancy           | 9.3 m²/person  |
|                   | people load         | 117.2 W        |
|                   | cooling system      | 3              |
|                   | heating system      | 0.8            |
| Infiltration      |                     | 2.19 m³/hr.m²  |
| Operation hours   | 9am–5pm             |                |
| Lighting control  | continuous dimming  |                |
|                   | (3 steps)           |                |

Figure 1. Skylight installed in a typical building ceiling layering scheme.  
Figure 2. Floor plan with illuminance measurement points and photo sensor.

Table 2. Energy simulation conditions.
density, occupancy and air infiltration were set to 11.34 W/m², 9.3 m²/person and 2.19 m³/hr.m², respectively based on common commercial buildings in South Korea [10]. A simplified HVAC system was designed, and it contained the outdoor air mixing box, coil cooling DX single speed, coil heating gas, a fan and air terminal. The cooling system used electricity with COP (Coefficient of Performance) of 3 while natural gas was used for heating system with COP of 0.8. Table 2 summarizes the simulation conditions used in this study.

3. Results and Discussion
The findings of this study were subdivided in the order of the steps followed in this study. First the energy performance of different SRRs under Ulsan climatic conditions with the assumption of no ceiling depth in the simulation model, followed by the inclusion of the ceiling depth in the simulation models of the pre-defined energy efficient SRRs. After that, a sensitivity analysis of the ceiling depth impact on skylight performance was done to further illustrate the results from previous steps. Finally, skylight daylighting performance and integrative optimization were carried out. The results from energy simulations are presented as the total building energy and lighting energy separately because adding a skylight to a building decreased its artificial energy demand while increasing the energy used for heating, cooling and ventilation. Therefore, for a skylight to be energy efficient, it had to outweigh the increased energy use by sufficiently reducing the need for artificial lighting. In this study, the total building energy consumption included the energy used for artificial lighting, heating, cooling and ventilation.

3.1. Skylight Energy Performance
The building energy consumptions were calculated using OpenStudio’s integrated Radiance and EnergyPlus simulation tools. The predicted energy consumption for different sized skylights were compared to the base model which had the same dimensions and materials properties but did not include any skylight. A skylight was called energy efficient if its energy consumption was less than that of the base model. As mentioned, for this first step, the energy performance of SRRs ranging from 1% to 25% were analyzed and no ceiling depth was included in the simulation models. Figure 3 shows the total and lighting energy for the 25 SRRs considered in this study. Adding a skylight to a building reduced its total building energy consumption and it reached its minimum at 6% SRR. Any skylight larger than 6% SRR minimally increased the total building energy consumption, however, all the SRRs below 20% were energy efficient compared to the base model. This special behaviour of the total building energy curve was caused by the fact that below 6% SRR, the reduction of the energy used for artificial lighting was sufficient to overcome the external conductance caused by the installation of a skylight into a building. However, as a skylight got larger, the reduction rate for lighting energy lowered while the external conductance was still increasing. Hence, the increased energy for heating, cooling and ventilation started to outweigh the energy saving from lighting. The optimal SRR was 6% with the energy reduction of 18% and 69% for the total building and lighting energy, respectively.

Figure 3. Predicted energy performance of skylights
3.2. Ceiling geometry and skylight performance

During this second step, the pre-defined energy efficient SRRs (from step1) were re-modeled with the ceiling depth included in the simulation models and their energy performance was re-evaluated. The ceiling depths considered in this study were 1.5 m, 2 m, 2.5 m and 3 m. Figure 4 illustrates how the energy performance of skylights changed as the ceiling got deeper. As expected, skylights performed poorer with the ceiling depth included in the simulation model than when no ceiling depth was included.

For a ceiling depth of 1.5 m, 2 m, 2.5 m and 3 m, the energy efficient SRRs were in the range of 1–17%, 5–17%, 7–17% and 9–17%, respectively. In terms of the total building energy consumption, the optimal SRR was 8%, 9%, 10% and 11% for a ceiling depth of 1.5 m, 2 m, 2.5 m and 3 m, respectively. The total building energy saved by the optimal SRRs were 9%, 7%, 5% and 3% for 1.5 m, 2 m, 2.5 m and 3 m ceiling depth, respectively. It is worth to point out that from the results, only one end of the energy efficient SRRs range (the minimum SRRs) changed as the ceiling depth increased suggesting for further investigations on this special characteristic of ceiling depth influence on the skylight energy performance. Thus, the next step was to perform a sensitivity analysis on how the impact of ceiling depth varied according to the size of the skylight.

![Figure 4](image-url)

(a) ceiling depth: 1.5m  (b) ceiling depth: 2m
(c) ceiling depth: 2.5m  (d) ceiling depth: 3m

**Figure 4.** Predicted energy performance of skylights according to different ceiling depths

3.3. Sensitivity analysis
The evaluation of skylight energy performance and the ceiling depth indicated that the performance of small skylights was more affected by the changes in the ceiling depth than it was for larger skylights. In order to elucidate the reason for this specific behavior, a sensitive analysis was performed to determine the contribution of the ceiling depth to the variance of the total and lighting energy consumption using statistical analysis software R. This software R has been widely used for sensitivity analysis of building energy related factors by various authors [11].

To increase the accuracy of the sensitivity results from R, more simulations with smaller ceiling depth variation were performed. For each SRR, a ceiling depth ranging from 1.5 to 3 m with the variation of 0.1 m (1.5, 1.6, 1.7, ..., 3 m) was applied. In order words, 20 alternatives for SRR (1–20% SRR) and 16 alternatives for ceiling depth were combined resulting into 320 simulations in total. The sensitivity index for this study was the regression coefficient and it was calculated for each SRR. Generally, a larger absolute value of regression coefficient indicates that the independent variable (ceiling depth) has greater impact on the dependent variables (lighting and total building energy).

Figure 5 shows how much lighting and total building energy changed with 0.1 m change in the ceiling depth according to the skylight size (SRR). Although the change in the total building energy was greater than lighting energy, they both followed a similar trend. The results indicated that the sensitivity of the ceiling depth increased as the SRR increased, in other words, as the daylight contribution to the reduction of the building energy increased. However, as the space got more saturated with daylight (SRR above 6%), the ceiling depth became less influential (decreased regression coefficient) on both lighting and total building energy consumption. The sensitivity analysis results explained why the energy performance of larger SRRs were less affected by the changes in the ceiling depth. The results also indicated that 6% SRR was more sensitive to the changes in the ceiling depth than it was for other SRRs.

Figure 5. Regression coefficient for 0.1m change in the ceiling depth.

3.4. Skylight daylighting performance and optimization

Building sustainability in regard to daylighting system is not merely about the energy efficiency but also the qualitative aspect of the daylight in buildings. Therefore, in this study, Useful Daylight Illuminance (UDI_{100–2000}) was used as the daylight metrics to evaluate the daylighting performance of skylights. Generally, a space is well daylit if more than a half of its floor area receives daylight illuminances in the range of 100 and 2000 lux for at least 50% of the annual occupied hours [8]. In addition, the metrics suggest that any illuminance above 2000 lux should be avoided as it increases glare probability. Hence, in this study, the percentage of the floor area receiving between 100-2000 lux from daylight for at least 50% of the occupied hours was calculated and any illuminance measurement point receiving above 2000 lux was eliminated from UDI_{100–2000} calculation. This means that the energy and daylighting optimization performed in this study was based on both the building energy efficiency and glare free building design.

Table 3 presents the results of daylighting performance evaluation for various SRRs and ceiling depths. The quality of the daylight from a skylight was graded as suitable “S” for UDI_{100–2000} above 50% with no illuminance greater than 2000 lux. Whereas the daylighting performance was graded as unsuitable
“N” for UDI_{100-2000} below 50% or if the space received illuminance above 2000 lux. For each ceiling depth, the pattern-shaded cells represent SRRs that were both energy efficient and suitable for adequate daylighting.

The results indicated that SRRs suitable for energy efficiency and adequate daylighting were 5–8%, 6–9%, 7–10% and 9–11% for 1.5 m, 2 m, 2.5 m and 3 m ceiling depth, respectively. Moreover, it is important to point out that the SRRs which had the best building energy reduction also were the ones with the highest UDI_{100-2000} suggesting that the UDI’s upper limit can also serve as an indication for energy efficient design. The energy and daylighting optimization concluded that the optimal SRRs were 8%, 9%, 10% and 11% with the total building energy reduction of 9%, 7%, 5% and 3% and UDI_{100-2000} of 95%, 95%, 87% and 87% for 1.5 m, 2 m, 2.5 m and 3 m ceiling depth, respectively.

Table 3. SRR and ceiling depth for suitable daylighting design

| Ceiling depth | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0m            | N | N | S | S | S | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.5m          | N | N | N | N | N | N | S | S | S | N | N | N | N | N | N | N | N | N | N | N |
| 2m            | N | N | N | N | S | S | S | S | S | N | N | N | N | N | N | N | N | N | N | N |
| 2.5m          | N | N | N | N | N | S | S | S | S | S | N | N | N | N | N | N | N | N | N | N |
| 3m            | N | N | N | N | N | N | S | S | S | S | S | N | N | N | N | N | N | N | N | N |

4. Conclusion

This study evaluated the impact of ceiling depth on both the energy and daylighting performance of horizontal skylights. Through Radiance and EnergyPlus simulation programs, the total building and lighting energy consumptions were predicted and the results showed that the ceiling depth had great influence on the skylight performance, thus it should not be excluded from simulation models with skylights, as it is often done for model simplicity. In addition, through a sensitivity analysis, the study induced that the ceiling depth became more influential as the size of the skylight increased, however, when the space got more saturated with daylight (SRR above 6%) the impact of the ceiling depth reduced. Through energy and daylight optimization, the study concluded that for a ceiling depth of 1.5 m, 2 m, 2.5 m and 3 m the optimal skylight to roof ratio was 8%, 9%, 10% and 11% with the total building energy reduction of 9%, 7%, 5%, and 3%, respectively. The calculated UDI_{100-2000} for the optimal skylight to roof ratio was 95%, 95%, 87%, and 86% for a ceiling depth of 1.5 m, 2 m, 2.5 m and 3 m, respectively. Furthermore, it is important to mention that there are other factors, such as the climatic conditions under consideration, model thermal and optical properties, and other simulation conditions that can slightly or greatly alter the energy predictions of skylights. Therefore, the authors’ future work will investigate the contribution of each of the main simulation input to the variance of the energy performance of skylights.

5. References

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