Thesis for the Degree of Master of Science

An Assessment of Ceiling Depth Effects on Skylight Daylighting and Energy Performance

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DEDICATION

This work is dedicated to my husband, Reverien Habimana and our daughter, Kyla Igaba. You have always been my pillar of strength. May the Lord bless and protect you!

An Assessment of Ceiling Depth Effects on Skylight Daylighting and Energy Performance

Abstract

The purpose of this study was to evaluate the impact of ceiling depth on both daylighting and energy performance of skylight. Through OpenStudio's integrated Radiance and EnergyPlus simulation programs, skylight daylighting and energy performance were assessed under two different local climate conditions of Ulsan and Seoul cities in South Korea. The influence of ceiling depth on skylight energy efficiency was analyzed by including ceiling depths of 1.5 m to 3 m into a simulation model with a skylight-to-roof ratios ranging from 1% to 20%. Through simulation predictions, energy efficient skylight-to-roof ratios were defined for each ceiling depth and for each of the two cities under consideration.

The results indicated that the energy performance of smaller apertures (small skylight-to-roof ratio) were more affected by the ceiling depth than were larger apertures and the range for energy efficient skylight-to-roof ratios became smaller as the ceiling depth increased. Under Ulsan climate conditions, the range for energy efficient skylight-to-roof ratios changed from 1–20%, when no ceiling depth was included into simulation model to 1–17%, 5–17%, 7–17%, and 9–17% for 1.5 m, 2 m, 2.5 m, and 3 m ceiling depth, respectively. The optimal skylight-to-roof ratio in terms of both daylighting and energy performance was 8%, 9%, 10%, and 11% for ceiling depths of 1.5 m, 2 m, 2.5 m, and 3 m, respectively. The results for Seoul climate conditions showed no energy efficient skylight-to-roof ratio for a ceiling depth greater than 2 m. The range for energy efficient skylight-to-roof ratios changed from 2-18%, when no ceiling depth was considered in the simulation, to 6-13% and 9-13% for a ceiling depth of 1.5 m and 2 m, respectively. The optimal skylight-to-roof ratio was 8% and 9% for 1.5 m and 2 m ceiling depth, respectively. This study induced that unlike side windows, ceiling depth plays a crucial role in daylighting and energy performance of a building with skylight. Actual solar heat gains and transmitted visible light can only be accurately reflected in simulation predictions when a ceiling depth is included into simulation model. Hence, ceiling should be carefully modeled for investigation involving top-lighting system.

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LIST OF ABBREVIATIONS

ASHRAE	The American Society of Heating, Refrigerating, and Air−Conditioning Engineers
COP	Coefficient of Performance
CDD	Cooling Degree Days
EUI	Energy Use Intensity
HDD	Heating Degree Days
HVAC	Heating, Ventilation, and Air Conditioning
IESNA	Illuminating Engineering Society of North America
SRC	Standard Regression Coefficient
SRR	Skylight−to−roof Ratio
UDI	Useful Daylight Illuminance

I. INTRODUCTION

1.1 Background

The increase in building energy consumption and the associated environment degradation have made numerous nations and building related institutions have an urge for sustainable building. Adequate daylighting has been proven to be among efficient ways to green building. The benefits of daylighting, when appropriately designed, in achieving significant building energy saving through reduced lighting energy have been studied and well documented by various researchers [1,2]. Besides its building energy saving potential, daylighting has been proven to enhance occupants' productivity and mood in offices and improve indoor environment in general [3]. Generally, daylight is introduced into a space through an opening in the building envelope, hence heat loss during cold season and heat gain during hot season. For this reason, daylighting systems are an essential part of modern architecture requiring much attention to balance the daylighting benefits and heat gain/loss associated with the system with the consideration of local climate conditions.

Top-lighting, one of various methods to introduce daylight into building, can improve indoor environment quality by providing fairly homogeneous illuminance distribution especially for building with no facades or in deep open space where natural light from side openings cannot reach the rear area of the space in sufficient amount. In addition, the wide variety of top−lighting strategies allow the system to be used for both aesthetic and energy−efficiency purposes [4,5]. Furthermore, the usefulness of top−lighting is expected to increase with the current urbanization rate. Sidker et al. [6,7], investigated urban energy optimization and suggested that for clustered buildings, case of a newly developing city, building shape, envelop, rooftops, orientation, and all other building regulations should be given more attention to efficiently reduce energy consumption. This study evaluates the impacts of ceiling geometry on lighting and total energy consumption of a building with horizontal skylight under two different climate conditions, in South Korea.

1.2 Problem Statement

The energy and daylighting performance of different daylighting systems can be evaluated through actual experiments, mock−up, or simulation programs. The latter are most preferred by both researchers and building designers due to their flexibility to evaluate various parameters with a lower cost and more time−efficient compared to actual experiments. In addition, with today's ascension in computational technology that has made various simulation programs available for engineers and designers to assess several features of building performance, building simulation has become an essential part of building early design stage.

For most of building simulation programs, the user is required to make some simplifications of the building. Research has reported that these simplifications and assumptions made during simulation can be among the source of inaccurate predictions from building simulation programs [6].

Generally, the physical model for building simulation does not include the envelop cross−sectional details, instead, these details are used as input to define building's thermal properties. With these modeling settings, scientific investigations can determine and discuss the amount of solar heat gains transmission as well as visible light that are reflected in the predictions from building simulations.

Unlike building side openings, skylights are generally accommodated in the roof of the building which is made of a layering scheme containing the building's systems such as ventilation and electric lighting, structure, and a hung−ceiling layer. Therefore, the effects of envelop related simplifications could be more significant for top−lighting compared to side windows. Hence, studies are needed to quantify the impact of modeling simplification on simulation predictions for designers and various researchers to make good use of the findings documented in the literature. With the knowledge of how much the predicted skylight performance is altered by ceiling depth, designers can direct their focus on other important aspects such as the cost and feasibility of possible adjustment of the ceiling depth through integration of two or more building functioning systems into one layer.

1.3 Research Objectives

Skylight can improve indoor lighting quality in the deep rear area of the space or in building lacking facades. However, its daylighting and energy performance depend on many factors such as the ceiling geometry, climate conditions, and the size of the aperture. The purpose of this study was to assess and parametrically evaluate the effect of the building envelop modeling settings in simulation tools on the skylight performance predictions through the consideration of a typical ceiling depth on horizontal skylight performance evaluation.

In order to consider both solar heat gain transmission (which are reflected in the space heating and cooling energy demand) and reflection of visible light from building envelop, indoor natural lighting quality, building lighting and overall energy consumption were assessed. Additionally, horizontal skylight optimization for both daylighting and energy performance was carried out for a typical ceiling depth. Moreover, given that local climate conditions play an important part in the performance of skylight, this study was conducted under two different cities of Souk Korea from two different climate zones.

1.4 Limitations

This study was based on computer simulations as any other kind of actual experiment could not been carried out. Also, no internal partitions or other structures were included in the simulation model to avoid any type of model complication which could markedly or slightly alter simulation predictions. In addition, considering that there could be other model simplification effects on side daylighting system, the model had no side windows for the analysis to be solely based on the ceiling depth impact on skylight performance predictions. Due to this no side windows assumption, energy performance of skylight was evaluated based on the study's base model rather than standards simulation model available online. The same method has been used in a previous study to purposely focus on the analysis of top−lighting system rather than top− and side−lighting combination [8].

II. LITERATURE REVIEW

2.1 Building and Daylight

2.1.1 Benefits of Daylight

Numerous studies have proven that natural light, when properly designed, can considerably improve occupant's productivity, mood, and health, and significantly reduce building energy demand. Holick [9] studied the benefits of solar radiation on human skin and found that solar radiation is at the base of Vitamin D production in human body. The study reported that solar radiation greatly contributes to human's well-being and general health through Vitamin production which reduces the risks of various diseases such as diabetes, tissue hardening, autoimmune disorder and cancer.

The benefits of natural light in building have been investigated extensively and are rather well documented. A review by Edwards and Torcellini [10] summarized the impacts of daylighting on building occupants. It was reported that workers in office with adequate daylighting were less likely to have frequent absenteeism, tiredness, eyestrain, bad mood, and poor performance at work. In addition, unlike artificial light, daylight's full spectrum characteristic makes it preeminent for a proper functioning of the human eyes. Moreover, daylight's various wavelengths positively influence human body's functions such as nervous and endocrine systems, circadian rhythms, etc. [10].

The advantages of daylight in different building categories have been investigated. Edwards and Torcellini [10] reported that natural light was proven to ameliorate patients both psychologically and physiologically in hospital wards and care homes. Adequate daylighting has been proven to contribute to pain and depression reduction and short period of stay in hospitals. A study on the effect of sunlight on postoperative patients by Walch et al.[11] concluded that patients in daylit hospital wards received 22% less pain-controlling pills compared to non-daylight hospitalization rooms. The correlation between indoor lighting quality and patient average length of stay (ALOS) in a healthcare facility was investigated by Choi et al. [12]. The study reported that patients admitted in hospital wards with better daylighting (southeast oriented rooms) stayed in the hospital 16 – 41% shorter time than the patients in northwest oriented hospital wards.

Regarding daylighting in office building, Leather et al. [13] reported that job quitting intention and job satisfaction were closely related to the quality of daylight entering working space. A great example of daylight benefits in office building is Lockheed's building 157 located in Sunnyvale, California. Sufficient daylight from wide windows and an atrium at the center significantly improved indoor lighting environment leading to 15% reduction in workers absence and 15% increase in productivity, hence the building won a defense contract of $ 1.5 billion [14]. In school, daylighting was proven to contribute to student's performance and health. A study on natural light importance in school reported that besides energy reduction, students from classrooms that used daylight scored higher in reading and mathematics subjects than students from classrooms with artificial lighting [15].

Daylight is among efficient ways to improve building energy performance through the reduction of energy used for artificial lighting which alone is responsible for around 25-40% of the total building energy consumption [16]. Lighting energy and total building energy consumption of Lockheed's building 157 were reduced by 75% and 50%, respectively [14]. Nonetheless, a review by Wong [17] indicated that the percentage of lighting energy saved highly depends on lighting control adopted and location of photo sensors.

Furthermore, daylight can contribute to building energy reduction by reducing internal heat gain from artificial lighting. However, openings in building envelop used to bring daylight into the space can be potential sources of heat gain and loss, thus an increased cooling and heating energy demand. Hence, great attention is needed when designing daylighting system of a building.

2.1.2 Daylighting Systems

Over the past years, various daylighting technics have been developed to enhance indoor lighting quality with a reduced building energy consumption. Daylighting system refers to any device or element located in or near building envelope with a primary use of bringing natural light into the building; side−lighting and top−lighting are the most common daylighting systems. Natural light is generally introduced into a space through side vertical openings, clerestory, lightwell and some other remote distribution systems.

A typical side−lighting system is the conventional openings in building facades known as vertical windows. For this type of daylighting system, the amount of daylight reaching the task level significantly reduces as the distance from the opening increases, thus for a deep and long room, the system results into poor daylighting at the room's rear area.

Skylight, an example of top−lighting system, refers to a sloped or horizontal opening on the roof of a building. Research have validated the usefulness of skylight in the provision of homogeneous illuminance distribution and reduction of building energy consumption. Unlike side openings, skylights are capable of bringing natural light even in deep rear area of the room at a sufficient amount resulting into improved indoor lighting conditions and artificial lighting energy reduction. Although there is no limitation on size and shape of building that can utilize skylights, much attention should be given to skylight configuration, size, glazing type, and local climate conditions[18]. Currently, construction market offers a great deal of options for skylight shape, size, and glazing materials that, if properly chosen, can eliminate skylight's constraint such as indoor overheating and visual discomfort.

2.1.3 Daylighting Performance Metrics

Generally, building performance metrics are the measures of the quality of a building regarding any given area such as energy consumption, indoor thermal condition, safety, etc. Performance metrics are usually applied in comparative analysis of different design features during building design phase or for benchmarking an existing building versus other buildings. Unlike other building performance, daylighting is extremely challenging to evaluate because the definition of "a good daylighting" varies depending on the aspect of daylight under consideration. Table 2.1 shows examples of different definitions given to daylighting for the five categories of sustainable building design [19].

Table 2.1. Five sample definitions of daylighting

Category	Daylighting definition
Architectural	The interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment.
Lighting	The replacement of indoor electric illuminance needs by daylight, resulting in reduced annual energy consumption for lighting.
Building energy	The use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting).
Load management	Dynamic control of fenestration and lighting to manage and control building peak electric demand and load shape.
Cost	The use of daylighting strategies to minimize operating costs and maximize output, sales, or productivity.

Daylighting performance metrics are sub-dived into static and dynamic daylighting performance metrics. The former is based on the evaluation of daylight under a given outdoor conditions while the later considers both seasonal and daily fluctuations in quantity and quality of daylight and irregular meteorological events of a site under consideration. Thus, dynamic daylighting metrics have been proven to be more accurate than static ones. Static daylighting metrics include Daylight Factor (DF), view to the outside and avoidance of direct sunlight; while dynamic daylighting metrics include Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Continuous Daylight

Autonomy (DA_{con}) and Annual Light Exposure.

Static daylight metrics:

I. Daylight Factor (DF): The daylight factor is expressed as the ratio of illuminance at a given point inside a space to the outdoor horizontal illuminance under CIE (Commission Internationale de l'Eclairage) overcast sky conditions. Although daylight factor has been widely used in daylighting evaluation, this metric was not initially developed to assess a good daylighting design. The metric was simply designed as a minimum legal lighting requirement [20]. Its calculation does not include direct solar radiation, time of the day and seasonal changes, variable sky conditions, building location and orientation. Hence, the daylight factor cannot be applied in the investigation of indoor glare problem or analysis of facade orientation impact on daylighting.

II. View to the outside: This is largely promoted in sustainable building design, acknowledging that a view to the outside is an important factor to occupant' s satisfaction to indoor environment. For instance, LEED (Leadership in Energy and Environmental Design) requires that a vertical opening between 76 cm and 228 cm above the floor is provided for all regularly occupied spaces. One of several limitations of this design criteria is that the benefits of a view greatly depend on the nature/type of view. In addition, the criteria get less important for building with interior shading devices that are more likely to remain lowered for most of occupied hours to avoid glare.

III. Avoidance of direct sunlight: This daylighting criteria is aimed to acknowledge research findings that direct sunlight is the main source of visual discomfort and it is usually used in parallel with daylight factor metric. The combination of daylight factor and avoidance of direct sunlight result into a building design with the least possible opening size to produce minimum acceptable daylight factor at area close to façade. One shortcoming of this method is that dynamic shading systems, such as venetian blinds, cannot be considered in this combined approach; only static shading devices are considered. Moreover, the actual climate, building type and occupant requirements are not considered by this approach.

Dynamic daylight performance metrics:

I. Daylight Autonomy (DA): The percentage of annual occupied hours when the daylight illuminance level at a given point in space is above the minimum required illuminance. The metric indicates the percentage of occupied times when the minimum required illuminance for a given task is met by natural lighting alone. The IESNA (Illuminating Engineering Society of North America) provides minimum illuminance levels required for different building types (Table 2.2).

II. Useful Daylight Illuminance (UDI): dynamic daylight metric based on task illuminance, has been developed in 2005 by Mardaljevic and Nabil. This criterion determines the percentage of occupied hours when the available daylight levels are between 100 lux and 2000 lux, a daylight useful range to the occupant. In other words, daylight levels below 100 lux is too dark while above 2000 lux the daylight is too bright and likely to cause glare. Based on this useful daylight levels range, UDI can be sub-divided into three metrics: percentage of hours when UDI fell-short (below 100 lux), was achieved (100-2000 lux), or was exceeded (above 2000 lux).

III. Continuous Daylight Autonomy (DA_{con}): this metric differs to Daylight Autonomy (DA) by the fact that it gives partial credit to time steps when available daylight illuminance levels are below minimum required values. For instance, DA_{con} gives 0.6 credits to a time step when daylight level at a given point is 300 lux in a space where 500 lux are required.

IV. Spatial Daylight Autonomy (sDA): the metric calculates the fraction of the space area where daylight autonomy is above a specified value. The calculation considers temporal and spatial characteristics of natural lighting.

V. Annual Sunlight Exposure: is expressed as the cumulative amount of daylight reaching on a given point over a period of one year. The metric is mostly used for the design of space with light-sensitive objects such as museum/ artwork exhibition hall.

Table 2.2. Examples of illuminance levels recommendation by IESNA.

Building type	Space type	Recommended Illuminance [lux]
Office	Open plan office area	300−500
	Conference room	300
	Lobby	100−200
Educational	classroom	400−500
	Computer room	300
Residence	Bedroom	300
	Laundry room	300
Hospital	General ward	300
	Examination room	500
Industrial	Metal working/welding	300
	Simple assembly	300
	Difficult assembly	1,000
	Exacting assembly	3,000−10,000

2.1.4 Daylighting Simulation Tools

Approximately, there exist more than 50 different methods to assess daylighting performance in buildings and these range from simple manual design tools to more complex computer−based tools [20]. Daylighting performance can be evaluated through actual experiment using full scale or mock−up models, scale models with sky simulators, analytical/ mathematical models, and computer simulation tools. The latter is the mostly used method due to its advantage of fast and accurate predictions involving various design parameters with a considerably low cost.

With today's computational advancements, several simulation programs are available, and they are all mainly based on two algorithms in their indoor daylighting calculations: radiosity (global illumination algorithm) and ray-tracing (direct illumination algorithm). Radiance, a backward ray-tracing based program, has been the most widely used modeling and simulation tool for daylighting performance evaluation and its accuracy was validated by various researchers [21]. Due to its lack of user interface, Radiance has been incorporated into several other computer programs as a lighting simulation engine to carry out dynamic daylight simulations (Table 2.3) [20].

Table 2.3. Simulation programs with Radiance as simulation engine for daylighting.

Program	Simulation engine	Dynamic simulation algorithm
Adeline	Radiance	Statistical sky
Spot	Radiance	Annual CIE sky simulation
Lightswitch Wizard	Radiance	Daylight coefficients and Perez
ESP-r	Radiance	Daylight coefficients and Perez
Daysim	Radiance	Daylight coefficients and Perez
OpenStudio	Radiance	Daylight coefficients and Perez

2.2 Building and Energy

2.2.1 Building Envelope and Energy Consumption

Innumerable research findings indicate that building sector is responsible for a significant portion of the global total energy consumption. Approximately, 20-40% of the total global energy is consumed by residential and commercial buildings alone with more than a half of that energy being used by HVAC (Heating, Ventilation, and Air Conditioning) systems [22]. Hence, building energy efficiency has been the main focus of global energy policies.

Building physics, composed of transparent, opaque or a combination of the two, greatly affect building energy performance through heating, cooling, and lighting energy consumptions. Building shape affects its energy performance by determining the amount of solar radiation received by the roof and facades total area. Orientation is another key parameter that impacts building energy efficiency by dictating how much direct solar radiations reach building facades. Therefore, thermal properties (mainly the heat transfer coefficient) of building envelope elements, such as foundation, walls, windows, and roof are carefully analyzed and optimized during design stage to control building heat losses/gains and occupant thermal comfort. Nonetheless, the efficacy of commonly used strategies to improve thermal performance of building envelope depends on building type, use schedule and local climatic conditions.

2.2.2 Energy Performance Metrics

In building sector, approaches to evaluate energy performance can be divided into two categories: feature−specific and performance−based approaches. In the latter approaches, the assessment is done by comparing performance index to the established benchmarks; while for feature−specific approaches, credits are given for each specific criteria met and those credits are summed up to give the final score of a building energy performance [23]. Currently, quantitative performance−based approaches are widely used, and buildings are evaluated based on standardized annual whole−building energy consumption metrics; Energy Use Intensity (EUI) is an example.

Energy Use Intensity (EUI) is expressed as the building annual total energy consumption divided by building total floor area. Many nations have established median EUI for various building types and those EUI are used to assess energy performance of any given building. Generally, EUI plays an important role during building design phase because design parameters are analyzed and optimized for lower EUI which indicates improved building energy performance.

2.2.3 Energy Simulation

Building energy simulation programs are used to detailedly predict energy required to achieve suitable building performance (both thermal and visual) under varying outdoor weather conditions, occupancy schedule, and various construction materials. During energy simulations, detailed heat-balance calculations are carried out over a course of a full year and the resulting predictions serve as pillars for decision making during building design stage. With building simulation tools, engineers and architects are no longer bound to the use of rule of thumb or mathematical calculations that were inefficient and source of inaccuracy. Simulation models allow various design parameters and energy conservation measures to be computed and optimized in time and cost-efficient manner.

They exist a lot of building simulation tools and more are being developed due to today's advancement in computer. Among the available energy simulation tools, we can name: EnergyPlus, IES-VE, TRNSYS, DEO-2.1e, TRACE 700, Energy 10, and HAP. Due to its availability, high accuracy, and capability to model multiple building service such as energy and water usage, EnergyPlus is one of the most whole-building energy simulation tools widely used by various engineers, architects, and researchers. EnergyPlus, funded by U.S. Department of Energy, has been validated through numerous research [24].

III. METHODOLOGY

3.1 Research Framework

3.1.1 Overview

This study analyzed the performance of horizontal skylight in terms of daylighting and building energy efficiency using building energy simulation tools under two different climate conditions. As illustrated in Figure 3.1, the study started by investigating the impact of SRRs (Skylight−to−roof ratio) and ceiling depth on predicted energy consumptions of a building with a horizontal skylight. A sensitivity analysis was used to quantify the significance of SRR and ceiling depth impact on building energy consumption. After this preliminary phase, the study was carried out in three different steps. First, energy efficient SRRs were defined through energy simulation models with the common assumption of no ceiling depth during simulation modeling. Second, a typical building ceiling depth was included in simulation models with the pre−defined energy efficient SRRs and the models' energy performance was re−evaluated. Third, daylighting performance was assessed, and optimal SRR−ceiling depth was determined.

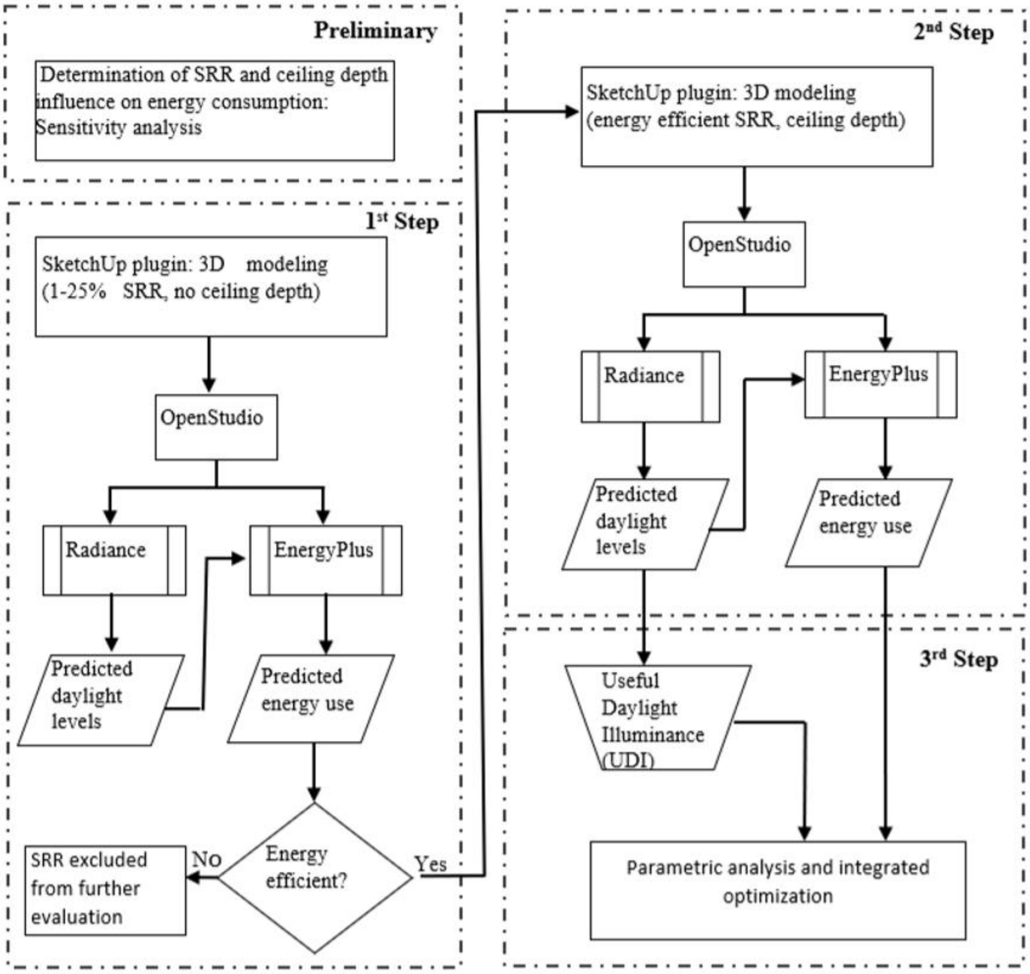


Figure 3.1. Flowchart of the study.

3.1.2 Integrated Daylighting and Energy Simulation

The energy saving benefits of daylight can only be fully achieved if proper lighting control system is installed. Daylighting sensor should be placed at an appropriate location to efficiently dim or turn off artificial lighting depending on available daylight levels. Hence, the need for whole building energy simulation programs to have a coherent package of tools to carry out daylighting and energy simulation. Generally, during daylighting simulation, hourly illuminance level at lighting sensor is calculated for the whole year, and a new artificial lighting schedule is created. This lighting load schedule is then used for building energy simulation (Figure 3.2). OpenStudio's integrated Radiance and EnergyPlus applies this method to carry out whole-building energy simulation.

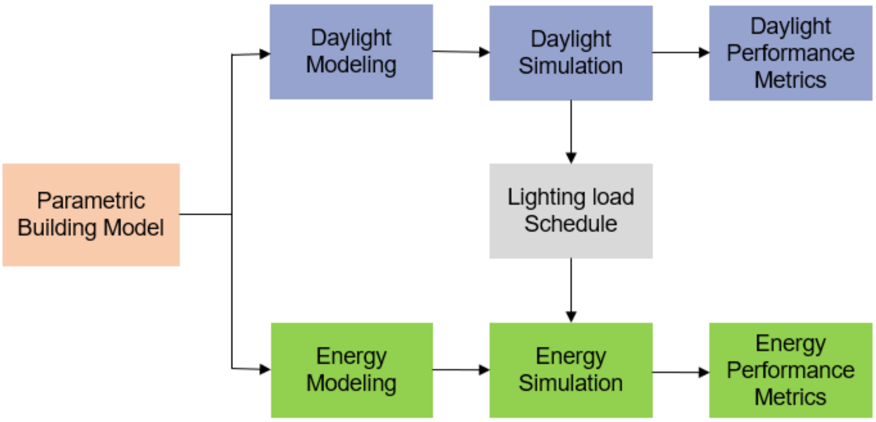


Figure 3.2. Integrated daylighting and energy in building simulation programs.

3.1.3 Sensitivity Analysis

Generally, in building energy investigations, sensitivity analysis is mostly used to determine how significant a certain input parameter is in influencing the output. In the current study, SRR and ceiling depth contribution on predicted building energy consumption was calculated through regression, assuming output-input variables' linear relationship. The output-input correlation is expressed by Equation (1) with an error variable ε_i, indicating the unobserved random variable.

$$y_i = \beta_1 x_{i1} + \beta_2 x_{i_2} + \varepsilon_i \qquad (i=1, 2, 3, \cdots, n) \qquad (1)$$

Where

y_i : predicted building energy consumption (lighting, cooling, heating, and total building energy)

β_1 and β_2 : regression coefficient for ceiling depth and SRR, respectively

x_{i1} : ceiling depth

x_{i_2} : SRR.

20 different skylight aperture sizes (1% to 20% SRR) combined with 16 alternatives for ceiling depth ranging from 1.5 m to 3 m (with a variation of 0.1 m) resulting into a total of 320 combinations (n=20 X 16=320). In addition, given that input and output parameters had different units, prior to regression, all the input and output variables were standardize using Equation (2).

$$x_{i1}' = \frac{x_{i1} - \bar{x}_1}{\delta_{x1}} \qquad x_{i2}' = \frac{x_{i2} - \bar{x}_2}{\delta_{x2}} \qquad y_i' = \frac{y_i - \bar{y}}{\delta_y} \qquad (2)$$

Where:

x_i' and y_i' : the standardized input and output,

x_i and y_i : the actual input and output,

$\bar{x}$ and $\bar{y}$: the input and output arithmetic mean,

δ_x *and* δ_y : the input and output standard deviation

Using Equation (3), standard regression coefficient (SRC) β_1 and β_2 were calculated and their values indicate the ceiling depth and SRR impact on the predicted energy consumption. The error variable was between 0.05 and 0.41 while the SRC varied between −1 and 1 with a larger absolute value denoting greater input influence on output.

$$\begin{bmatrix} Y_1^{'} \\ \cdots \\ Y_n^{'} \end{bmatrix} = \begin{bmatrix} x_{11}^{'} & x_{12}^{'} \\ \cdots & \cdots \\ x_{n1}^{'} & x_{n2}^{'} \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \cdots \\ \varepsilon_n \end{bmatrix} \qquad (3)$$

3.2 Research Design

3.2.1 Case Study Model and Variables

This study evaluated energy performance of 9 m × 9 m × 4.5 m open space representing a small scale of vast open rooflit space of a single-story building or a top floor of a multi-story building. The model had no internal partitions, columns, or any other type of structure to avoid any influence that they could have on the output. The model dimensions were defined referring to a previous top-lighting related study[25]. The main objective of this study was to assess the energy and daylighting performance of skylight; hence simulation model had no side openings (only top-lighting was included into simulation model). Due to this side-lighting exclusion, the models' energy performance could not be computed against the available standard simulation models;

instead, the study's base model was used to determine energy efficiency of case models. The method of evaluating energy performance of top-lighting system using a base model has been applied in another study regarding skylight [8]. The 4.5 m floor-to-ceiling height was used to ensure that most of natural light at the task level depended on skylight and ceiling components.

The optical properties of model materials were selected based on IESNA (Illuminating Engineering Society of North America [26]. Walls, floor, and ceiling light reflectance was set to 50%, 30%, and 70%, respectively. Materials thermal transmittance selected based on Korean Energy-Saving Design criteria for office and commercial buildings[27], for walls, floor, and ceiling was set to 0.429 W/m^2K, 0.513 W/m^2K, and 0.192 W/m^2K, respectively.

A glazing material with low thermal transfer and high daylight transmittance was selected to minimize indoor-outdoor heat exchange. A previous study by Yoon et al. [28]on skylight energy performance under five different climate conditions reported that a flat-styled CoolOptics, manufactured by SunOptics, was more energy efficient when used for horizontal skylight; hence the material was selected for this study. The thermal transmittance, shading coefficient, and visible transmittance of the glazing material were 1.98 W/m^2K, 0.37, and 0.67, respectively. The optical and thermal properties of the simulation model are summarized in Table 3.1.

Table 3.1. Model's thermal and optical properties

Element	Material	Reflectance	U−value [W/m2K]	Visible transmittance	Shading coefficient
Floor	Brick + heavyweight concrete + insulation	0.3	0.513	−	−
Walls	Heavy concrete + insulation	0.5	0.429	−	−
Ceiling	Lightweight concrete + insulation	0.7	0.192	−	−
Glazing	Flat−styled CoolOptics	−	1.98	0.67	0.37

As previously mentioned, this study investigated the impact of ceiling depth on skylight energy and daylighting performance. A building ceiling deep enough to accommodate different building elements such as roof structure and insulation, and building functioning system such as ventilation, electric lighting, and any other mechanical system. Although building ceiling geometry may differ depending on the type and size of a building, a typical ceiling depth ranging from 1.5 m and 3 m was considered in this study [29]. A layering scheme of a typical ceiling and the study variables are presented in Figure 3.3.

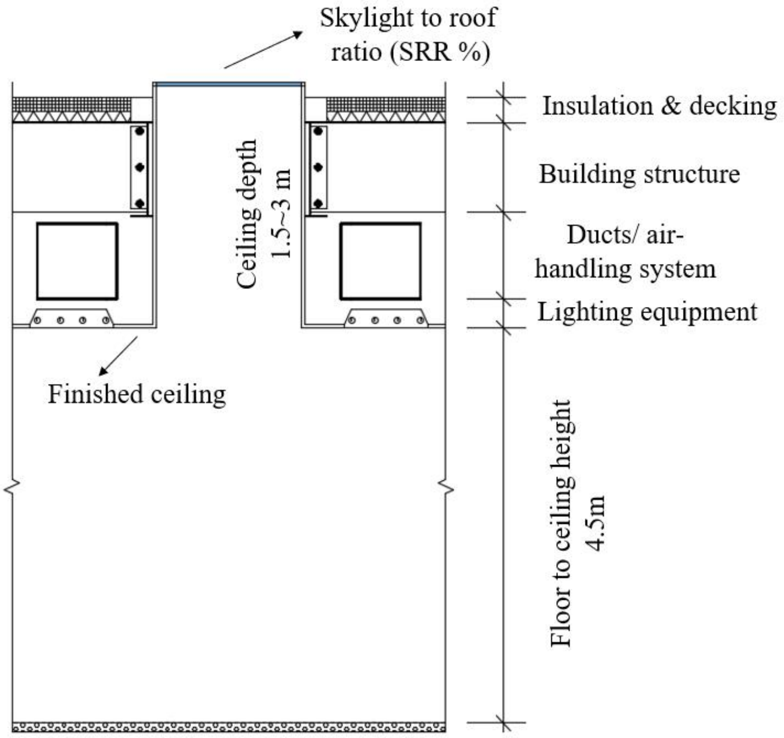


Figure 3.3. A horizontal skylight accommodated in a ceiling layering scheme.

3.2.2 Skylight and Climate Conditions

Various investigations have reported a critical role played by local climate conditions in energy performance of skylights [8,30]. Therefore, it was important for this study to evaluate if this climate impact is still reflected even with the inclusion of ceiling depth into simulation model. Hence, this study was carried out considering two Korean cities, Ulsan and Seoul, from different Korean climate zones. Currently, South Korea is subdivided into three climate zones, namely Central, Southern, and Jeju[31]. Based on Köppen climate classification, Korean Central climate zone is classified as Dwa with cold−dry winter and hot−summer while the Southern and Jeju climate zones are classified as Cfa with humid year−round and hot summer [31]. As illustrated on Figure 3.4, the two cities used in this study were selected from the Central and Southern climate zone as these two zones represent the biggest part of the country. Moreover, Southern and Jeju climate zones are in the same Köppen classification, thus one city from either climate zone was enough for the purpose of this study. The CDD (cooling degree days) for Ulsan and Seoul are 659.4 and 881.2, respectively while their HDD (heating degree days) are 2013.9 and 2626.8, respectively [32].

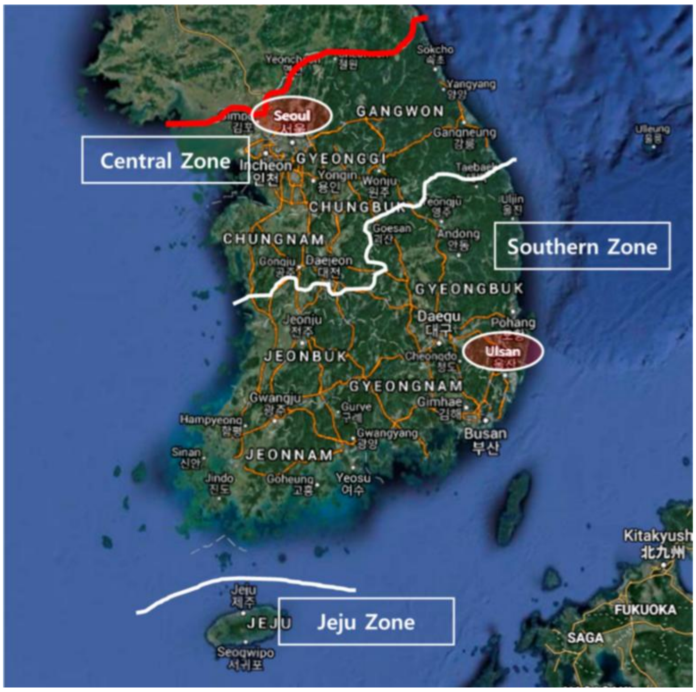


Figure 3.4. Three Korean climate zones and the two cities selected for the study.

3.2.3 Simulation Tools and Modeling Conditions

The model simulations were carried out through OpenStudio's integrated Radiance and EnergyPlus [33]. This simulation tool was purposely chosen to avoid separate daylighting and energy simulation which often reduces predictions' accuracy. A previous study on daylighting and energy performance of building fenestration has confirmed the accuracy of integrated Radiance and EnergyPlus for simulation of complex building design [34].

Using OpenStudio SketchUp plugin, a simulation model was created with all compatible elements for a light−backwards ray−tracing calculation method used by Radiance. A daylighting photosensor and illuminance map of 81 measurement points were included in the model for artificial lighting control and daylighting qualitative analysis, respectively. A study by Nabil and Mardaljevic[35] reported that for accurate daylighting analysis, the distance between side wall and contour illuminance measurement points should be about 0.5 m and the distance between two consecutive measurement points should be 1 m. In addition, sensor for lighting control should be placed where daylighting illuminance levels are likely to be the lowest. Figure 3.5 displays the 81 measurement points and daylighting photosensor's location. During trial simulation, Radiance parameters were constantly modified until more consistent predictions were obtained.

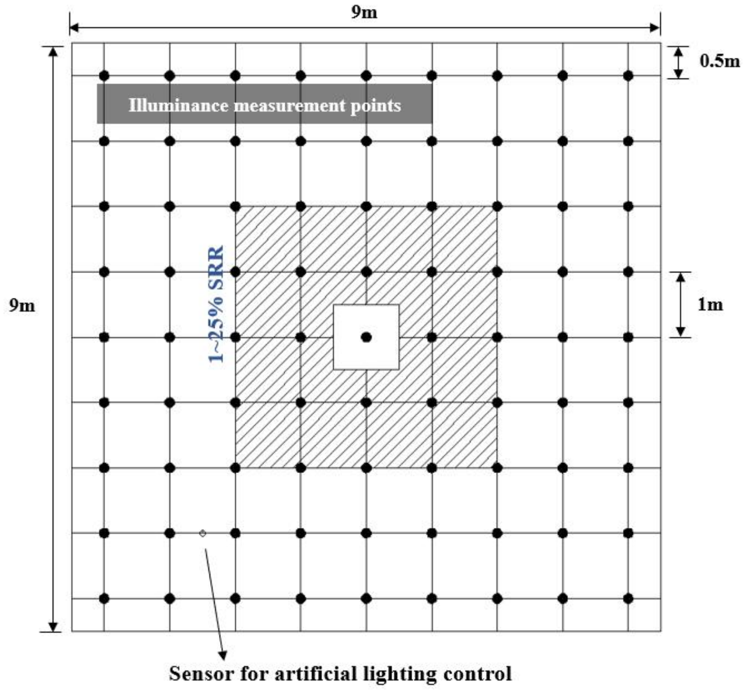


Figure 3.5. Illuminance map and location of daylighting photosensor point.

The model's artificial lighting was controlled by a stepped dimming control system with three steps. A general open space lighting recommendation of 300 lux by IES (Illuminating Engineering Society) was used for illuminance set point. Artificial lighting fixtures were dimmed in discrete and equally spaced steps from their maximum to zero input power as the daylight at the photosensor increased. As illustrated on Figure 3.6, artificial lighting input power was dimmed to 1, 2/3, 1/3, and 0, for daylight illuminance range of 0–100 lux, 100–200 lux, 200–300 lux, and above 300 lux, respectively.

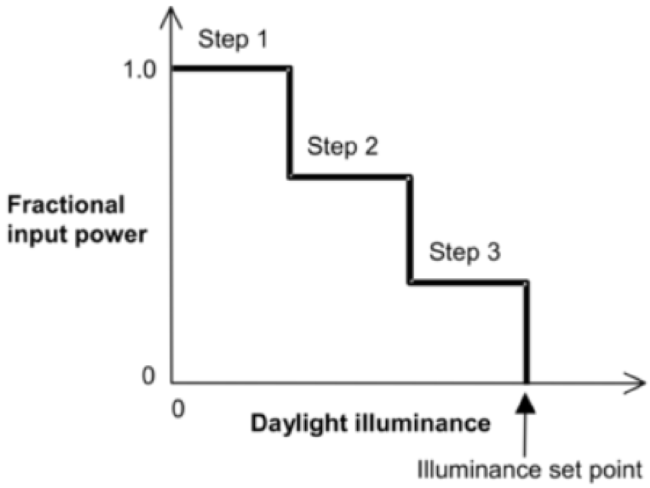


Figure 3.6. Stepped artificial lighting control with three steps

From SketchUp plugin, simulation model was imported into OpenStudio where it was further modified by defining materials' optical and thermal properties and all other input parameters necessary for whole building energy simulation. Through OpenStudio-to-Radiance forward translator, OpenStudio model (.osm) was translated into a valid Radiance model and daylighting simulation was carried out. During this first phase of simulation, hourly daylight illuminance reaching at the photosensor was used to calculate a new artificial lighting schedule that was forwarded back to the OpenStudio model. This new generated lighting schedule was used by EnergyPlus during whole building energy simulation.

The type of weather data plays a key role in accuracy of predictions from building simulations and ASHRAE (the American Society of Heating, Refrigerating, and Air-conditioning Engineers) gives recommendation of weather data to be used for energy simulation [36]. In the current study, International Weather for Energy Calculations (IWEC), weather data suitable to represent a typical long-term weather patterns, was used. The model has only one thermal zone and both people and lighting were considered for internal loads. Model's lighting power density, occupancy, and air infiltration was set to 11.34 W/m^2, 9.3 m^2/person, and 2.19 m^3/hr.m^2, respectively based on a typical commercial building in South Korea[37]. The model included one simple HVAC system composed of an outdoor air mixing box, a DX single-speed cooling coil, coil heating gas, a fan, and an air terminal. The electricity and natural gas were used for cooling and heating system, respectively. The coefficient of performance (COP) for cooling and heating system was 3 and 0.8, respectively. The summary of input values and simulation conditions is presented in Table 3.2.

Table 3.2. Simulation input and modeling conditions.

Category	Input	Values
Setpoint	Lighting	300 lux
	Cooling	24^0C
	Heating	20^0C
Internal loads	Lighting density	11.34 W/m^2
	Occupancy	9.3 m^2/person
	People load	117.2 W
COP	Cooling system	3
	Heating system	0.8
Infiltration	–	2.19 m^3/hr.m^2
Operation hours	9am – 5pm	–
Lighting control	Stepped dimming	–

IV. RESULTS

4.1 Sensitivity Analysis

The impact of ceiling depth and SRR on lighting, cooling, heating, and total building energy consumption was evaluated through standard regression coefficient (SRC) with a higher SRC absolute value indicating greater impact. From sensitivity results in Figure 4.1, it was observed that the skylight's lighting energy reduction benefit (negative SRC value) can be outweighed by its increase in heating energy consumption (positive SRC value). This observation suggested that skylight energy performance was highly dependent of local weather conditions. Hence, this study was conducted for two South Korean cities, Ulsan and Seoul, with different climate conditions.

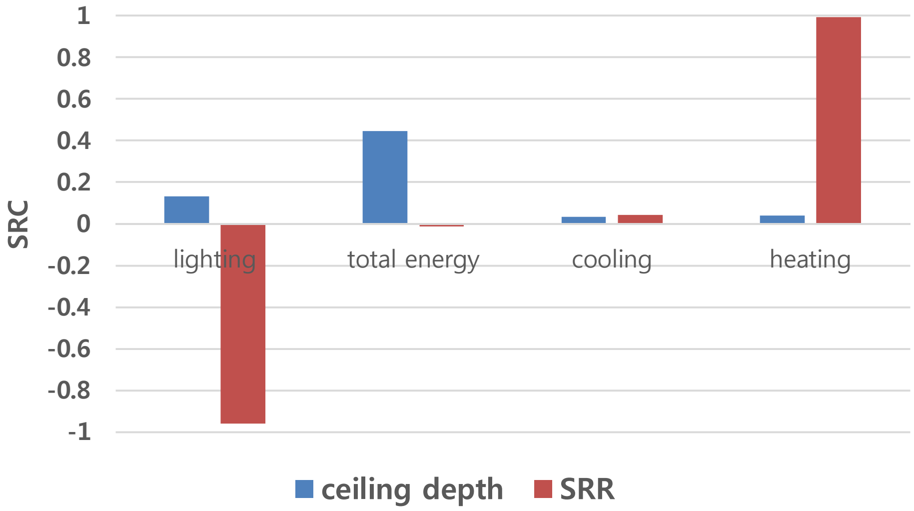


Figure 4.1. Results of standard regression coefficient.

Sensitivity analysis also showed that energy performance of a building with skylight was negatively affected by the ceiling depth. It is important to mention that the ceiling depth's impact on the total building energy consumption was greater than the sum of the ceiling depth's impact on single energy consumption (lighting, cooling, and heating). This could be explained by the fact that the increase in artificial lighting resulted in an increased internal load from artificial lighting and this was reflected in total building energy consumption. Despite a low impact on both cooling and heating energy consumption, sensitivity results indicate that the ceiling depth can significantly alter skylight energy performance by influencing lighting and total building energy consumption. Hence, further analysis on skylight energy performance with ceiling depth included in simulation model was carried out in the next phase of the study.

4.2 Skylight Performance and Climate Conditions

4.2.1 Skylight Energy Efficiency in Ulsan

As mentioned in the previous chapter, in order to define energy efficient skylight, SRR (skylight-to-roof ratio) ranging from 1% to 25% were evaluated. Energy consumption for each SRR was predicted through OpenStudio's integrated Radiance and EnergyPlus. SRR's energy performance was analyzed and benchmarked against a base model, that had the same materials' optical and thermal properties and dimensions but did not include a skylight. For an SRR to be considered as energy efficient, its energy consumption should be less than that of the base model.

Figure 4.2 illustrates energy performance of skylight under Ulsan weather conditions. Skylight impact on building energy is evaluated not only in terms of total energy consumption, but also in individual building energy consumption (electric lighting, heating, cooling, and ventilation). The results indicated that cooling energy consumption minimally reduced as the SRR increased until it reached its minimum at 4% SRR and from there the cooling energy linearly and slowly increased as the SRR increased. These results were in a good agreement with previous investigations on skylight under different climate conditions. A study by Ghobad et al. [30] reported that skylight with SRR less than 3.5% reduced cooling energy under Miami and Boston climate conditions. Another evaluation of skylight under San Francisco climate conditions revealed that the cooling load was minimally increased for a 5% SRR[8].

Regarding space heating, results indicated a more steadily and conspicuously increased heating energy consumption with SRR increase. This was caused by an increased thermal conductance as the size of the skylight increased. Although the energy consumed for space ventilation followed a similar trend as cooling, the trend was more conspicuous for ventilation as it contributed more to the total building energy consumption than did cooling. The increase in SRR reduced lighting energy consumption with no fluctuations. However, this lighting energy reduction showed an explicit behavior that significantly influenced the overall skylight energy performance.

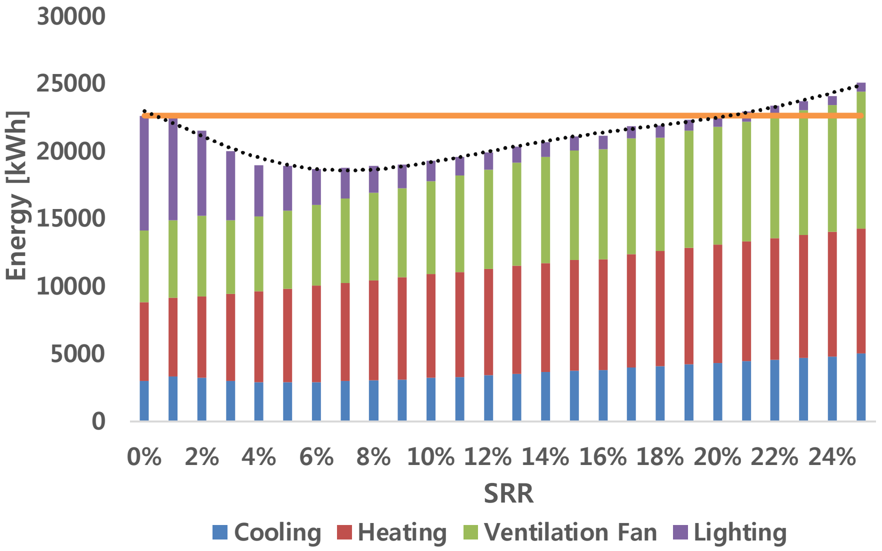


Figure 4.2. Skylight energy performance under Ulsan climate conditions.

As it can be seen from Figure 4.2, the reduction rate for lighting energy consumption was more important and noticeable for smaller apertures; this reduction rate slowly reduced as SRR increased. This is explained as daylight saturation phenomenon. As SRR increased, more daylight entered into the space and daylight illuminance levels received by the electric lighting control point approached the illuminance set value (300 lux in this study) for most of the occupied hours, hence any increase in SRR made less to none contribution on lighting energy reduction. The total energy consumption decreased when the skylight size was increased, and it reached it minimum value at a 6% SRR. The results indicated that for any skylight with SRR greater than 6%, lighting energy reduction was outweighed by the increased cooling, heating, and ventilation energy consumption. Nonetheless, any skylight with SRR below 20% was more energy efficient compared to the base model. Hence, for Ulsan climate conditions, SRRs from 1% to 20% were considered as energy efficient with 6% SRR an optimum skylight-to-roof ratio. The electric lighting and total building energy reduction of optimal SRR was 68.5% and 18%, respectively.

4.2.2 Skylight Energy Efficiency in Seoul

The results of predicted skylight energy performance under Seoul climate conditions are illustrated in Figure 4.3. The general trend for energy reduction and increase was similar to that of Ulsan, however, the building consumed moderately more energy due to higher number of HDD and CDD compared to Ulsan. The results showed that, unlike under Ulsan climate conditions, the total building energy was slightly increased for 1% SRR. This was caused by the fact that for such a small aperture, the insignificant reduction in lighting energy could not offset the increase in heating energy which dominates the total building energy consumption in the case of Seoul. These results supported other findings that skylights are more energy efficient in non-heating dominated climates.

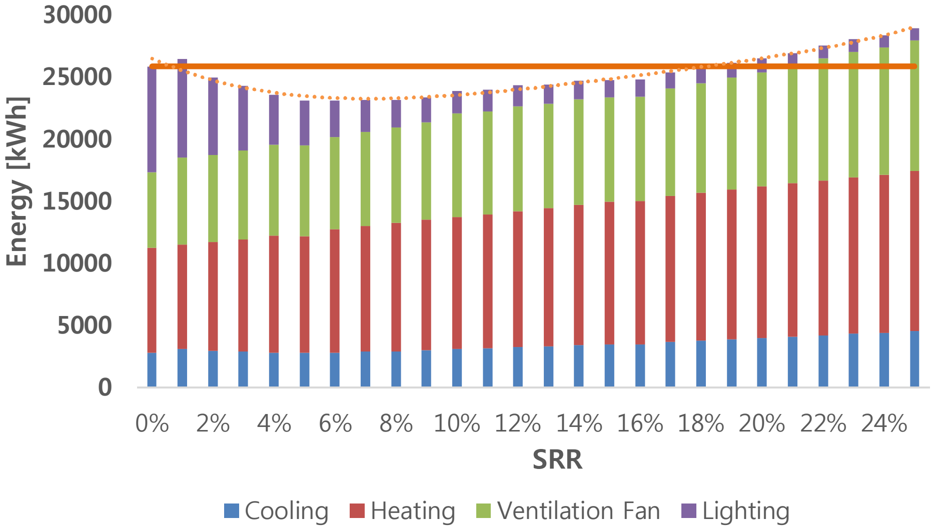


Figure 4.3. Skylight energy performance under Seoul climate conditions.

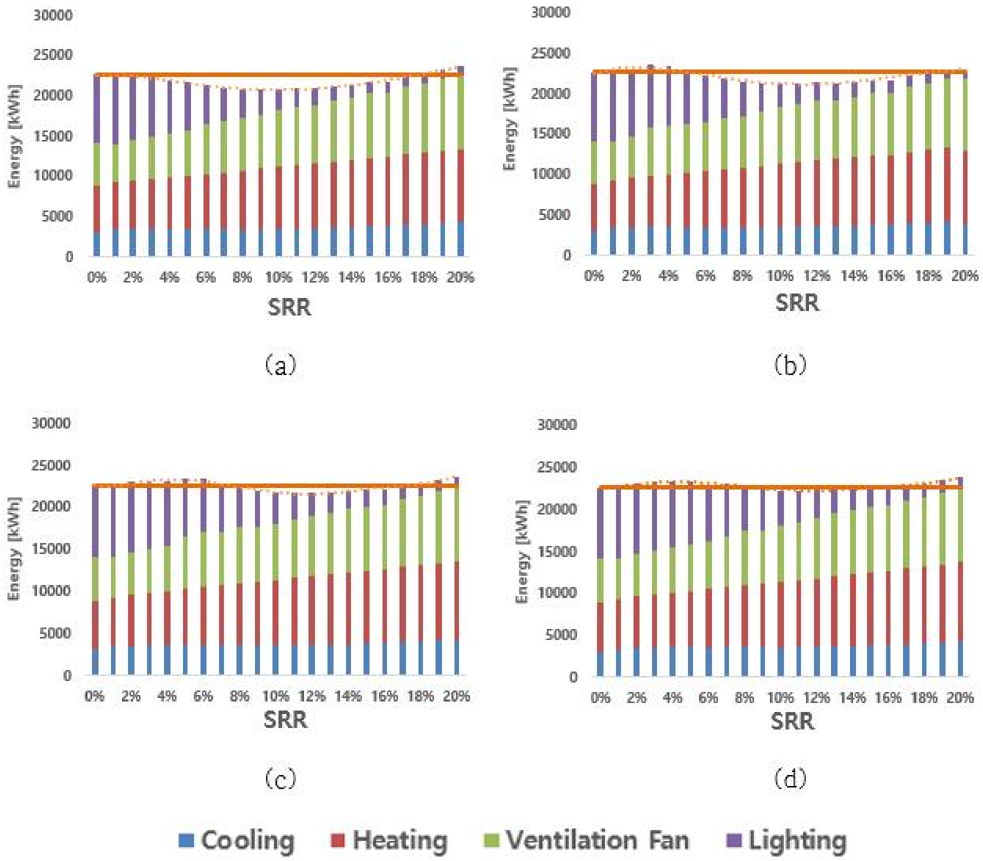
The total energy consumption reduced as the SRR increased, and it reached its minimum value at 6% SRR. As shown in Figure 4.3, any increase of SRR above 6% resulted into an increased total energy consumption. However, all the SRRs in the range of 2% and 18% were defined as energy efficient as their total energy consumption were less than the base model. It is important to mention that although both Ulsan and Seoul had the same optimum SRR (6%), lighting and total energy reduction for the optimal SRR was small for Seoul climate conditions. Under Seoul climate conditions, optimal SRR reduced lighting and total energy consumption up to 11% and 65.5%, respectively.

4.3 Ceiling Depth and Skylight Energy Performance

4.3.1 Ceiling Depth and Skylight Energy Efficiency in Ulsan

As previously mentioned, this study analyzed energy performance of horizontal skylight considering conditions in which it is installed. Unlike side-windows, skylights are accommodated in building ceiling. Depending on the size of the building and equipment to be installed in the ceiling, vertical dimension of a building ceiling layering scheme can be between 1.52 m and 2.74 m [29]. Thus, four different ceiling depth were considered in this study: 1.5 m, 2 m, 2.5 m, and 3 m.

During this step of the study, each of the pre-defined energy efficient SRRs (1% to 20% SRR) were remodeled with the inclusion of ceiling depth into simulation model. Through simulation results, the impact of ceiling depth on skylight energy performance was assessed. Figure 4.4 illustrates the variation of skylight energy efficiency according to ceiling depth.



(a) (b)

(c) (d)

Figure 4.4. Skylight energy performance under Ulsan climate conditions with a ceiling depth: a) 1.5m, b) 2m, c) 2.5m and d) 3m.

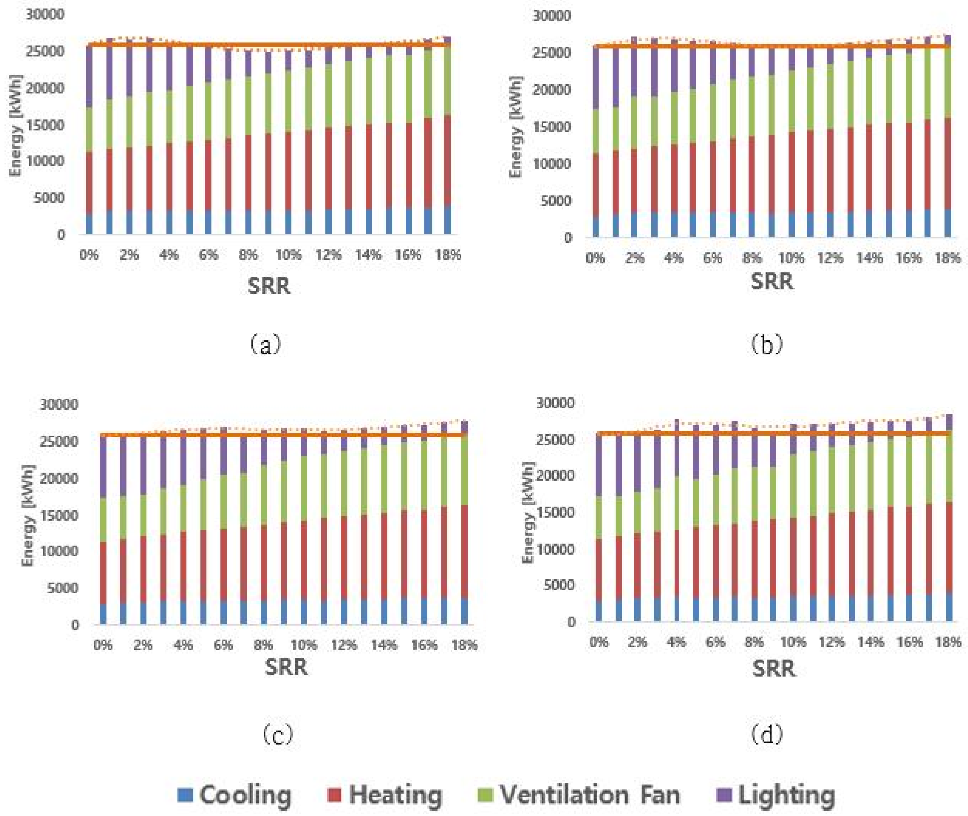
As shown in Figure 4.4, a building ceiling depth significantly affect energy performance of a skylight. Results indicated that lighting and total building energy consumption increased as the building ceiling got deeper. Generally, as the ceiling depth increased daylight was forced to undergo multiple reflection on the vertical section of the ceiling before reaching the occupied space, hence the daylight illuminance levels received by lighting control sensor diminished resulting into an increased lighting and total building energy consumption.

It is important to mention that this ceiling depth impact on skylight energy performance was more conspicuous for smaller aperture than it was for larger ones. Results showed that the ranges of energy efficient SRRs changed from 1–20% to 1–17%, 5–17%, 7–17%, and 9–17% for 1.5 m, 2 m, 2.5 m, and 3 m ceiling depth, respectively. Note that only one side of the energy efficient SRRs actively changed (the minimum energy efficient SRR) as the ceiling depth changed. This specific behavior was attributed to the fact that the smaller the aperture, the more daylight bounces prior to reaching workspace. Hence, the ability for skylight to considerably reduce lighting energy and outweigh the thermal exchange was notably lessened for smaller skylights as the ceiling depth increased. Nonetheless, for SRR greater than 17%, the increase in heating, cooling, and space ventilation energy consumption could not be offset by lighting energy reduction, therefore 18% to 20% SRRs were no longer energy efficient.

In addition, these results showed that the optimum SRR changed as the ceiling depth increased. For a ceiling depth of 1.5 m, 2 m, 2.5 m, and 3 m, the optimum SRR was 8%, 9%, 10%, and 11%, respectively. Moreover, the total building energy saved by optimum SRR reduced as the ceiling depth increased. Building energy was reduced up to 9%, 7%, 5%, and 3% for optimum SRR with ceiling depth of 1.5 m, 2 m, 2.5 m, and 3 m, respectively.

4.3.2 Ceiling Depth and Skylight Energy Efficient in Seoul

The evaluation of ceiling depth impact on skylight energy performance under Seoul climate conditions was conducted following the same procedures as for Ulsan. Four different ceiling depth (1.5 m, 2 m, 2.5 m, and 3 m) were included into simulation model for each of the predefined energy efficient SRRs (2–18%), then energy consumptions were predicted through building energy simulation. The results are displayed in Figure 4.5.



(a) (b)

(c) (d)

Figure 4.5. Skylight energy performance under Seoul climate conditions with a ceiling depth: a) 1.5m, b) 2m, c) 2.5m and d) 3m.

The ceiling impact on skylight energy performance under Seoul climate conditions was not different from that of Ulsan. However, due to their difference in building heating energy demand (HDD for Seoul and Ulsan are 2626.8 and 2013.9, respectively), the ceiling effect was even more manifested under Seoul climate conditions.

Both the reduction in solar heat gain (through daylight reflection) and increased thermal conductance negatively affected heating energy consumption making it harder for skylight to perform efficiently. Hence, for a city with a relatively higher heating energy demand compared to Ulsan, only fewer SRRs were energy efficient. Results showed that energy efficient SRRs changed from 2–18% to 6–13% and 9–13%, for a ceiling depth of 1.5 m and 2 m, respectively. No skylight was energy efficient for ceiling depths of 2.5 m and 3 m. The optimum SRR was 8% and 9% with a total energy reduction of 4% and 1% for ceiling depth of 1.5 m and 2 m, respectively.

4.4 Ceiling Depth and Skylight Daylighting Performance

4.4.1 Skylight Daylighting Performance in Ulsan

$UDI_{100-2000}$(Useful Daylight Illuminance) was used to evaluate daylighting performance of skylight. In this study, any daylight illuminance levels below 100 lux were considered insufficient to provide adequate lighting or give any reduction in lighting energy consumption. On the other hand, daylight illuminance greater than 2 000 lux was considered as a source of glare, hence for sustainable design no one of the 81 measurement points should receive illuminance above 2 000 lux. For qualitative analysis, skylight daylighting was defined as suitable if more than 50% of the space received daylight illuminance levels between 100 lux and 2 000 lux for at least 50% of the annual occupied hours without exceeding 2 000 lux at any point in the space [34]. For each SRR and ceiling combination, the percentage of floor area with daylight illuminance in the range of 100–2 000 lux was calculated, and the results are displayed in Table 4.1.

Table 4.1. UDI [%] for skylight and ceiling depth under Ulsan climate conditions.

SRR [%]	Ceiling depth				
	0m	1.5m	2m	2.5m	3m
1	8	0	0	0	0
2	40	11	5	1	0
3	71	26	13	11	11
4	92	41	27	26	16
5	100	55	45	31	26
6	96	72	55	54	32
7	87	86	71	55	45
8	81	95	84	65	55
9	74	92	95	84	65
10	70	90	90	87	82
11	57	86	90	94	86
12	63	80	89	90	95
13	55	74	79	87	96
14	47	73	75	86	90
15	38	66	74	75	84
16	42	66	72	74	83
17	24	55	69	70	73
18	20	52	58	69	71
19	17	45	53	65	69
20	13	43	50	54	66

The grey and orange shaded area in Table 4.1 represents a poor and excessive daylighting, respectively, while the blue shaded area indicates suitable daylighting. Daylighting performance results showed that adequate daylighting SRR range changed from 3–5% (when no ceiling depth is included into the simulation model) to 5–8%, 6–9%, 6–10%, and 8–11% for ceiling depths of 1.5 m, 2 m, 2.5 m, and 3 m, respectively.

4.4.2 Skylight Daylighting Performance in Seoul

The evaluation of daylighting performance was carried out using $UDI_{100-2000}$ in the same way as for Ulsan. Table 4.2 shows the calculated percentage of floor area where daylighting illuminance levels are between 100 lux and 2 000 lux for at least 50% of annual occupied hours. Floor area with illuminance below 100 lux or above 2 000 lux were excluded from calculations.

Table 4.2. UDI [%] for skylight and ceiling depth
under Seoul climate conditions.

SRR [%]	Ceiling depth				
	0m	1.5m	2m	2.5m	3m
1	11	0	0	0	0
2	38	8	3	1	0
3	71	24	13	11	11
4	91	42	28	26	14
5	100	53	45	31	26
6	94	69	55	44	31
7	89	77	69	54	45
8	84	94	85	69	55
9	75	90	94	84	64
10	74	89	94	92	82
11	69	86	89	92	85
12	58	82	89	90	91
13	53	74	84	90	91
14	51	73	75	84	90
15	45	66	71	77	87
16	38	66	74	74	86
17	27	62	68	70	73
18	21	58	65	69	70
19	16	52	55	65	69
20	13	43	48	58	69

In Table 4.2, the blue and yellow shaded area represent SRR–ceiling depth combinations with poor and excessive daylight, respectively. The green shaded area indicates SRR–ceiling depth combinations with adequate daylighting performance. Adequate daylighting was defined as the one having more than 50% of the floor area receiving daylight illuminance values between 100 and 2 000 lux without exceeding 2 000 lux at any occupied hour. As it can be seen from the table, the SRR range for adequate daylighting changed from 3–5% (when no ceiling depth was included into the simulation model) to 5–8%, 6–9%, 7–10%, and 8–11% for a ceiling depth of 1.5 m, 2 m, 2.5 m, and 3 m, respectively.

4.5 Skylight Daylighting and Energy Optimization

4.5.1 Skylight Optimization in Ulsan

Both provision of adequate natural lighting and energy efficiency are among the key important features of building sustainability. Generally, the quantity of daylight introduced into a space can be enhanced by increasing the size of the opening in the building envelope. However, given that building envelop plays a crucial role in determining its energy efficiency, an optimization of the opening size and building energy consumption resulting from thermal exchange is needed to balance the benefits and drawbacks of daylighting systems.

In this study, skylight optimization was carried out based on $UDI_{100-2000}$ and total building energy reduction. As discussed earlier, UDI_{100-}

$_{2000}$ of 50 with no daylight illuminance above 2000 lux (excessive illuminance) was considered suitable daylighting. Regarding energy reduction, for each SRR, percentage of energy reduction was calculated based on the base model which had same dimensions and material properties but did not include a skylight. Optimization results are presented in Table 4.3. Note that only up to 12% SRR are presented in the table because daylighting was inadequate for all SRRs greater than 11%.

Table 4.3. Integrated daylighting and energy skylight optimization in Ulsan.

Ceiling depth [m]		**SRR [%]**											
		1	2	3	4	5	6	7	8	9	10	11	12
0	UDI[%]	P	P	71	92	100	E	E	E	E	E	E	E
	Energy*	2.4	4.8	11	16.3	17.6	17.9	16.5	16.4	16	14.7	13.4	11.9
1.5	UDI[%]	P	P	P	P	55	72	86	95	E	E	E	E
	Energy*	0.2	0.8	1.6	3.2	4.4	5.6	7.4	9.2	8.7	8.2	7.9	7.6
2	UDI[%]	P	P	P	P	P	55	71	84	95	E	E	E
	Energy*	–	–	–	–	1.0	2.2	3.6	5.0	7.1	6.1	6.0	5.6
2.5	UDI[%]	P	P	P	P	P	54	55	65	84	87	E	E
	Energy*	–	–	–	–	–	–	0.5	1.3	3.1	5.2	4.1	4.0
3	UDI[%]	P	P	P	P	P	P	P	55	65	82	86	E
	Energy*	–	–	–	–	–	–	–	–	0.5	1.9	3	1.4

Energy*: percentage of energy reduced compared to the base model.

In Table 4.3, SRR–ceiling depth combinations with UDI$_{100\text{–}2000}$ less than 50 and daylight illuminance value above 2000 lux are indicated by

P (poor daylight) and E (excessive daylight), respectively. The shaded area in the table represents SRR–ceiling depth possible alternatives for adequate daylighting and energy reduction.

It was interesting to observe that for all the combinations, the highest $UDI_{100-2000}$ was linked the optimum energy reduction. This argues that the upper limit for $UDI_{100-2000}$ can be also applied as a threshold for building energy efficiency. It was noticed that for any SRR greater than the one with highest $UDI_{100-2000}$ there was excessive daylight, solar heat gains and thermal conductance. The daylight−energy optimal SRR was 5% with $UDI_{100-2000}$ and energy reduction of 100 and 17.6%, respectively, when no ceiling depth was included into simulation model. The optimal SRRs were 8%, 9%, 10%, and 11% with UDI of 95, 95, 87, and 86 and total building energy reduction of 9%, 7%, 5%, and 3%, for ceiling depths of 1.5 m, 2 m, 2.5 m, and 3 m, respectively.

4.5.2 Skylight Optimization in Seoul

Daylighting and energy performance optimization of skylight under Seoul climate conditions was done in the same way as for Ulsan and the results are displayed in Table 4.4. As mentioned previously, $UDI_{100-2000}$ less than 50 and daylight illuminance levels above 2000 lux are indicated by P (poor daylighting) and E (excessive daylighting) in the optimization results table.

Table 4.4. Integrated daylighting and energy skylight optimization in Seoul.

Ceiling depth [m]		SRR [%]											
		1	2	3	4	5	6	7	8	9	10	11	12
0	UDI[%]	P	P	71	91	100	E	E	E	E	E	E	E
	Energy*	–	3.5	6	8.8	10.6	11.5	10.4	10.4	9.5	7.5	7.2	5.9
1.5	UDI[%]	P	P	P	P	53	69	77	94	E	E	E	E
	Energy*	–	–	–	–	–	0.7	1.5	4.2	3.1	2.9	1.1	0.5
2	UDI[%]	P	P	P	P	P	55	69	85	94	E	E	E
	Energy*	–	–	–	–	–	–	–	–	1.1	0.5	0.1	–
2.5	UDI[%]	P	P	P	P	P	P	54	69	84	92	E	E
	Energy*	–	–	–	–	–	–	–	–	–	–	–	–
3	UDI[%]	P	P	P	P	P	P	P	55	64	82	85	E
	Energy*	–	–	–	–	–	–	–	–	–	–	–	–

Energy*: percentage of energy reduced compared to the base model.

In this study's optimization, a SRR–ceiling depth combination was considered as a possible alternative if it was both suitable for adequate daylighting ($\text{UDI}_{100–2000}$ higher than 50 with no illuminance above 2000 lux) and energy efficient (less energy consumption compared to the base model. As it can be seen from Table 4.4, although for 2.5 m and 3 m ceiling depths no SRR were energy efficient, 7–10% and 8–11% SRRs met $\text{UDI}_{100–2000}$ criteria for adequate daylighting.

Nonetheless, no possible SRR alternatives for sustainable skylight in a ceiling deeper than 2 m was obtained under Seoul climate conditions. Optimization results indicated that 5% SRR was optimum with $\text{UDI}_{100–2000}$ and energy reduction of 100 and 10.6% when no ceiling depth was considered in simulation model. After including a ceiling depth into simulation, the optimum SRR changed to 8% and 9% for a ceiling depth of 1.5 m and 2 m, respectively. Optimal SRRs had $UDI_{100-2000}$ of 94 and total building energy reduction of 4.2% and 1.1% for ceiling depths of 1.5 m and 2 m, respectively.

V. CONCLUSIONS

5.1 Conclusions

The purpose of this study was to investigate the impact of common simulation modeling simplifications on predicted energy and daylighting performance of skylight. Through OpenStudio's integrated Radiance and EnergyPlus, both daylighting and energy performance were assessed, and an integrated optimization was carried. The study concluded that skylight-to-roof ratios in the range of 5–6% which as reported elsewhere as ideal skylight size with the best energy and daylighting performance could be optimal only when no ceiling depth was considered in simulation model. Results from this study exhibited a critical role played by ceiling depth in determining energy and daylighting performance of skylight; hence any simulation model involving skylight investigation should not exclude ceiling geometry related parameters, as it is often done for modeling simplification purpose.

Skylight performance in two cities (Ulsan and Seoul) from two different climate zones in Korea and a ceiling depth of 1.5 to 3 m were considered in this study. Through integrated daylighting and energy optimization method, the study concluded that optimum skylight-to-roof ratio changed from 5% (when no ceiling depth was included into simulation model) to 8%, 9%, 10%, and 11% with total building energy reduction changing from 18% to 9%, 7%, 5%, and 3% for ceiling depths of 1.5 m, 2 m, 2.5 m, and 3 m, respectively under Ulsan climate conditions. In the case of Seoul, optimum skylight-to-roof ratio changed from 5% to 8% and 9% with total building energy reduction changing from 11% to 4% and 1% for ceiling depths of 1.5 m and 2 m, respectively. In addition, no energy efficient skylight-to-roof ratio was obtained for a ceiling deeper than 2m under Seoul climate conditions.

Even though the inclusion of a ceiling depth into simulation model showed a similar change in skylight performance for the two cities considered, generally, skylights were more energy efficient under Ulsan climate conditions than Seoul. With 95% of the space area receiving suitable daylighting (illuminance levels between 100 and 2000 lux) for at least 50% of occupied hours, the highest total energy reduction was 9% and 4% under Ulsan and Seoul climate conditions, respectively.

This study induced that for a top-lighting system, transmitted visible light and solar heat gains could be fully accounted for when a ceiling depth was included into simulation model. Ceiling depth influences skylight's performance by altering its potential to provide adequate daylighting and solar heat gains through several light reflection on the vertical section of the ceiling. Considering a critical role played by solar heat gains in counterbalancing thermal conductance caused by skylight, the extent to which ceiling depth impact the overall skylight energy performance is highly depend on the climate conditions under consideration. For climate conditions with more heating energy demand, designers are recommended to first define maximum ceiling depth for energy efficient skylight then proceed with exploration of possible ways of integrating different ceiling layers to reduce the ceiling depth.

5.2 Future Studies

The results of this study indicated that skylight performance was affected by only changing modeling simplification of one of many physical properties of simulation model (ceiling depth). Hence, it could be interesting to investigate how other simplifications such as building geometry, site neighborhood and building functioning systems such as HVAC system would impact skylight performance. Future work should elaborate the sensitivity of simulation model with related factors on daylighting and energy performance of skylights and their optimization.

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Appendix A

Energy consumption[kWh] for no ceiling depth under Ulsan climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2982.261	5820.482	5295.932	8498.123	22596.79863
1%	3316.555	5817.471	5726.9962	7741.562	22602.58475
2%	3202.191	6034.271	5982.1159	6290.019	21508.59776
3%	2999.855	6404.638	5445.4849	5137.582	19987.56043
4%	2876.694	6759.95	5498.2683	3809.2	18944.11238
5%	2903.086	6916.528	5744.5907	3334.15	18898.35401
6%	2911.883	7115.261	5982.1159	2674.358	18683.61772
7%	2973.463	7268.828	6228.4383	2296.077	18766.80668
8%	3026.247	7401.317	6501.1524	1961.782	18890.49845
9%	3096.625	7542.839	6615.5164	1724.257	18979.23741
10%	3202.191	7675.328	6888.2305	1495.529	19261.2793
11%	3290.164	7762.651	7125.7557	1389.962	19568.53232
12%	3395.73	7859.006	7354.4837	1293.193	19902.41314
13%	3527.689	7973.429	7627.1978	1178.829	20307.14402
14%	3633.256	8078.818	7864.723	1064.465	20641.26096
15%	3765.214	8175.173	8111.0454	1029.276	21080.70853
16%	3782.809	8193.24	8155.0315	1011.681	21142.76136
17%	4002.739	8379.929	8559.7041	888.5202	21830.89246
18%	4073.117	8518.44	8410.1512	862.1285	21863.83694
19%	4213.873	8635.874	8630.0819	826.9396	22306.76785
20%	4319.44	8762.34	8682.8653	782.9534	22547.59859
21%	4442.601	8867.729	8876.4043	756.5617	22943.29613
22%	4565.762	8988.174	9061.1461	721.3728	23336.45478
23%	4680.126	9090.552	9237.0907	694.9811	23702.74952
24%	4803.287	9195.941	9404.2381	677.3867	24080.8526
25%	5005.623	9244.119	10143.205	659.7922	25052.73949

Appendix B

Energy consumption[kWh] for 1.5m ceiling depth under Ulsan climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2982.261	5820.482	5295.932	8498.123	22596.79863
1%	3325.353	5877.694	4741.7066	8339.773	22284.52616
2%	3378.136	6037.283	4988.029	7996.681	22400.12903
3%	3395.73	6260.105	5207.9597	7363.281	22227.07611
4%	3351.744	6476.905	5445.4849	6580.327	21854.46193
5%	3351.744	6678.65	5603.835	5964.521	21598.75061
6%	3325.353	6895.45	6105.2771	4996.826	21322.90595
7%	3298.961	7154.406	6351.5995	4108.306	20913.27229
8%	3272.569	7368.195	6457.1663	3501.297	20599.22759
9%	3316.555	7563.917	6738.6776	2991.058	20610.20815
10%	3378.136	7747.595	7002.5945	2603.98	20732.30547
11%	3422.122	7892.129	7240.1197	2252.091	20806.46109
12%	3474.906	8060.751	7284.1058	1988.174	20807.93609
13%	3536.486	8208.295	7548.0227	1706.662	20999.4668
14%	3633.256	8331.751	7785.5479	1548.312	21298.86704
15%	3738.822	8452.196	8031.8703	1442.746	21665.634
16%	3747.62	8485.318	8067.0592	1372.368	21672.36456
17%	3941.159	8690.074	8489.3262	1222.815	22343.37343
18%	4037.928	8807.507	8709.257	1143.64	22698.33205
19%	4169.887	8939.996	8973.1738	1055.668	23138.72407
20%	4275.453	9048.396	9193.1046	1002.884	23519.83826

Appendix C

Energy consumption[kWh] for 2m ceiling depth under Ulsan climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2982.261	5820.482	5295.932	8498.123	22596.79863
1%	3351.744	5880.705	4882.4622	8392.557	22507.46801
2%	3457.311	6034.271	5190.3653	8216.612	22898.55999
3%	3580.472	6121.594	6087.6826	7759.156	23548.90495
4%	3562.878	6347.427	6140.466	7169.742	23220.51302
5%	3448.514	6654.561	6026.102	6219.641	22348.81788
6%	3439.717	6838.239	6061.291	5753.388	22092.63434
7%	3430.919	7115.261	6377.9912	4838.476	21762.64797
8%	3430.919	7353.139	6290.0189	4372.223	21446.30049
9%	3395.73	7569.939	6729.8804	3410.094	21105.64474
10%	3439.717	7783.728	6993.7973	2982.261	21199.50307
11%	3474.906	7952.351	7231.3225	2577.588	21236.16699
12%	3527.689	8087.851	7460.0504	2278.482	21354.07264
13%	3571.675	8298.629	7213.728	2146.524	21230.55587
14%	3615.661	8461.229	7433.6587	1803.432	21313.98094
15%	3712.431	8587.696	7671.1839	1671.474	21642.78398
16%	3721.228	8617.807	7715.1701	1601.096	21655.30066
17%	3888.375	8852.674	8111.0454	1363.571	22215.66499
18%	3993.942	8964.085	8322.1789	1293.193	22573.39861
19%	4099.509	9108.618	8577.2985	1161.234	22946.66002
20%	3668.445	9232.074	8788.432	1055.668	22744.6182

Appendix D

Energy consumption[kWh] for 2.5m ceiling depth under Ulsan climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2982.261	5820.482	5295.932	8498.123	22596.7986
1%	3334.15	5928.883	4724.1121	8392.557	22379.7012
2%	3448.514	6076.427	5076.0013	8295.787	22896.7294
3%	3510.094	6245.049	5295.932	8005.479	23056.5546
4%	3527.689	6458.839	5348.7154	7583.212	22918.4544
5%	3615.661	6597.35	6202.0466	6923.419	23338.477
6%	3650.85	6793.072	6501.1524	6421.977	23367.052
7%	3536.486	7088.161	6342.8023	5515.863	22483.3124
8%	3527.689	7320.017	6712.2859	4724.112	22284.1039
9%	3501.297	7551.873	6597.9219	4222.67	21873.7619
10%	3492.5	7765.662	6685.8942	3694.836	21638.8923
11%	3536.486	7976.44	6914.6222	3228.583	21656.1312
12%	3562.878	8157.107	7134.5529	2788.722	21643.259
13%	3598.067	8349.818	7389.6726	2322.469	21660.0257
14%	3650.85	8497.362	7618.4005	2172.916	21939.5287
15%	3756.417	8672.007	7653.5895	1970.579	22052.5926
16%	3747.62	8696.096	7697.5756	1891.404	22032.6954
17%	3888.375	8946.018	8093.4509	1548.312	22476.1569
18%	3985.145	9075.496	8304.5844	1425.151	22790.3766
19%	4099.509	9232.074	8559.7041	1319.584	23210.8713
20%	4187.481	9367.574	8770.8376	1187.626	23513.5188

Appendix E

Energy consumption[kWh] for 3m ceiling depth under Ulsan climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2982.261	5820.482	5295.932	8498.123	22596.7986
1%	3351.744	5940.927	4882.4622	8445.34	22620.4737
2%	3457.311	6115.572	5067.2041	8357.368	22997.4545
3%	3527.689	6302.261	5234.3514	8119.843	23184.1435
4%	3571.675	6482.927	5410.296	7820.737	23285.6353
5%	3589.27	6687.683	5551.0517	7389.673	23217.6769
6%	3562.878	6955.672	5683.0101	6633.111	22834.671
7%	3624.458	7079.128	5973.3187	6369.194	23046.099
8%	3624.458	7313.995	6465.9635	5471.877	22876.2933
9%	3589.27	7554.884	6421.9774	4908.854	22474.9846
10%	3554.081	7792.762	6677.097	4125.901	22149.8399
11%	3571.675	8003.54	6905.825	3580.472	22061.5121
12%	3633.256	8114.951	7125.7557	3404.528	22278.49
13%	3694.836	8385.951	7389.6726	2859.1	22329.5595
14%	3721.228	8587.696	7618.4005	2384.049	22311.3734
15%	3791.606	8711.151	7855.9257	2225.699	22584.382
16%	3791.606	8765.351	7891.1146	2067.349	22515.4208
17%	3914.767	9048.396	8084.6537	1777.04	22824.8571
18%	3993.942	9177.874	8286.99	1627.487	23086.2935
19%	4090.712	9352.519	8542.1096	1460.34	23445.6799
20%	4178.684	9488.019	8753.2431	1319.584	23739.5301

Appendix F

Energy consumption[kWh] for no ceiling depth under Seoul climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2797.519	8449.185	6087.6826	8498.123	25832.5095
1%	3131.814	8385.951	7002.5944	7917.506	26437.8655
2%	2973.463	8741.263	7002.5944	6202.047	24919.3671
3%	2885.491	9048.396	7160.9446	5172.771	24267.6027
4%	2815.113	9421.774	7310.4975	4002.739	23550.1244
5%	2806.316	9373.596	7284.1058	3624.458	23088.4768
6%	2823.911	9924.63	7424.8615	2829.477	23002.8795
7%	2876.694	10138.42	7556.8199	2551.196	23123.1296
8%	2911.883	10331.13	7662.3866	2234.496	23139.8962
9%	2991.058	10499.75	7838.3312	2032.16	23361.3020
10%	3096.625	10617.19	8330.9761	1829.824	23874.6107
11%	3158.205	10785.81	8286.9899	1724.257	23955.2608
12%	3254.975	10909.26	8454.1373	1689.068	24307.4444
13%	3316.555	11117.03	8383.7594	1548.312	24365.6583
14%	3413.325	11264.58	8498.1234	1495.529	24671.5530
15%	3474.906	11463.31	8392.5567	1389.962	24720.7336
16%	3492.5	11499.44	8427.7456	1354.773	24774.4614
17%	3659.647	11767.43	8647.6763	1284.395	25359.1508
18%	3756.417	11899.92	8823.6209	1231.612	25711.5705
19%	3870.781	12071.55	9025.9572	1161.234	26129.5264
20%	3967.55	12213.08	9157.91566	1126.045	26464.5878
21%	4073.117	12348.58	9404.23808	1082.059	26907.9909
22%	4205.076	12459.99	9826.50508	1038.073	27529.6414
23%	4319.44	12577.42	10099.2192	1020.479	28016.5585
24%	4416.209	12721.95	10239.9749	985.2897	28363.4282
25%	4539.37	12863.48	10547.8779	950.1008	28900.8259

Appendix G

Energy consumption[kWh] for 1.5m ceiling depth under Seoul climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2797.519	8449.185	6087.6826	8498.123	25832.5096
1%	3254.975	8388.962	6747.4748	8366.165	26757.577
2%	3272.569	8644.907	6958.6083	7855.926	26732.0103
3%	3298.961	8834.607	7336.8892	7380.875	26851.3326
4%	3228.583	9192.93	7336.8892	6474.761	26233.1627
5%	3228.583	9463.93	7512.8338	5841.36	26046.7069
6%	3158.205	9728.908	7873.5202	4882.462	25643.0955
7%	3158.205	10030.02	8058.262	4187.481	25433.9676
8%	3167.003	10304.03	8023.0731	3507.62	25001.7257
9%	3167.003	10605.14	8163.8288	3079.03	25015.0033
10%	3210.989	10827.96	8357.3678	2683.155	25079.4756
11%	3263.772	11008.63	8515.7179	2472.021	25260.1424
12%	3342.947	11165.21	8682.8653	2340.063	25531.0843
13%	3404.528	11391.04	8823.6209	2058.552	25677.7428
14%	3483.703	11553.64	8999.5655	1952.985	25989.8958
15%	3562.878	11734.31	9131.524	1829.824	26258.5349
16%	3562.878	11782.49	9096.3351	1768.243	26209.9432
17%	3703.634	12113.71	9281.0769	1592.298	26690.7186
18%	3765.214	12499.13	9307.4686	1504.326	27076.1411

Appendix H

Energy consumption[kWh] for 2m ceiling depth under Seoul climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2797.519	8449.185	6087.6826	8498.123	25832.50955
1%	3149.408	8575.651	5788.5769	8401.354	25914.99018
2%	3316.555	8653.94	6985	8111.045	27066.5411
3%	3334.15	8927.952	6861.8388	7829.534	26953.47434
4%	3307.758	9220.03	7108.1612	7055.378	26691.32691
5%	3316.555	9478.985	7257.7141	6536.341	26589.59627
6%	3281.367	9716.863	7759.1562	5683.01	26440.39615
7%	3281.367	10002.92	7935.1008	5014.421	26233.8071
8%	3263.772	10298.01	8278.1927	4205.076	26045.04861
9%	3219.786	10593.1	8225.4094	3580.472	25618.76494
10%	3281.367	10876.14	8445.3401	3096.625	25699.47334
11%	3325.353	11086.92	8612.4874	2762.33	25787.09007
12%	3378.136	11252.53	8770.8376	2395.183	25796.68746
13%	3457.311	11472.34	8855.5794	2137.657	25822.89044
14%	3510.094	11680.11	9087.5378	2102.538	26380.27944
15%	3589.27	11848.73	9254.6852	2023.363	26716.04915
16%	3606.864	11881.85	9281.0769	1979.377	26749.1714
17%	3730.025	12225.12	9465.8187	1750.649	27171.6134
18%	3800.403	12399.77	9580.1827	1645.082	27425.43305

Appendix I

Energy consumption[kWh] for 2.5m ceiling depth under Seoul climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2797.519	8449.185	6087.6826	8498.123	25832.5096
1%	3149.408	8614.796	5788.5769	8418.948	25971.7291
2%	3184.597	8900.852	5647.8212	8260.598	25993.868
3%	3272.569	9096.574	6184.4522	7917.506	26471.1017
4%	3290.164	9352.519	6369.194	7477.645	26489.5212
5%	3360.542	9560.285	6923.4194	6985	26829.2465
6%	3378.136	9752.997	7363.2809	6465.964	26960.3771
7%	3272.569	10126.37	7222.5252	5559.849	26181.3182
8%	3334.15	10285.96	8155.0315	4891.259	26666.4047
9%	3404.528	10584.06	8348.5706	4425.006	26762.1686
10%	3404.528	10827.96	8779.6348	3721.228	26733.3547
11%	3378.136	11147.14	8700.4597	3123.016	26348.7544
12%	3439.717	11330.82	8876.4043	2920.68	26567.6213
13%	3501.297	11553.64	9061.1461	2647.966	26764.052
14%	3554.081	11764.42	9210.699	2392.846	26922.0465
15%	3615.661	11972.19	9360.2519	2181.713	27129.8134
16%	3633.256	11996.28	9404.2381	2181.713	27215.4829
17%	3765.214	12336.53	9659.3577	1952.985	27714.0888
18%	3809.2	12541.29	9703.3439	1759.446	27813.2778

Appendix J

Energy consumption[kWh] for 3m ceiling depth under Seoul climate conditions.

SRR	Cooling	Heating	Ventilation Fan	Lighting	Total energy
0%	2797.519	8449.185	6087.6826	8498.123	25832.5096
1%	3114.219	8805.129	5454.2821	8462.935	25836.565
2%	3193.394	8958.063	5656.6184	8313.382	26121.457
3%	3263.772	9171.852	5850.1575	8172.626	26458.4073
4%	3457.311	9238.096	7222.5252	7873.52	27791.4528
5%	3369.339	9635.563	6571.5303	7363.281	26939.7132
6%	3369.339	9882.475	6958.6083	6721.083	26931.5049
7%	3483.703	10045.07	7512.8338	6492.355	27533.9665
8%	3334.15	10484.7	7372.0781	5287.135	26478.0601
9%	3298.961	10758.71	7134.5529	4900.057	26092.2792
10%	3457.311	10900.23	8621.2847	4213.873	27192.6995
11%	3483.703	11092.94	8806.0265	3888.375	27271.0468
12%	3510.094	11354.91	9166.7129	3272.569	27304.2857
13%	3536.486	11634.94	9140.3212	2929.477	27241.2273
14%	3589.27	11845.72	9307.4686	2691.952	27434.4108
15%	3659.647	12047.47	9474.6159	2498.413	27680.1416
16%	3668.445	12110.7	9501.0076	2392.846	27672.9971
17%	3782.809	12478.05	9764.9245	2084.943	28110.7308
18%	3853.186	12649.69	9905.6801	1988.174	28396.7283