# Development and Performance evaluation of Daylight Duct System with Multiple Light Distribution Modules

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## Abstract

Recently, the consumption of energy in buildings for lighting purposes has been on the rise, which has led to an increase in research to find solutions to this issue. In this area of research, daylight ducts have been recognized for their efficiency as natural lighting systems, and have been the subject of various studies. Despite this, daylight ducts are limited in terms of their ability to improve upon lighting performance due to their application of single light distribution modules. Considering this, this research proposed a daylight duct system with multiple light distribution modules, and subjected the system to a performance evaluation to validate its effectiveness. To undertake the performance evaluation in this study, the light environment simulation program known as Radiance was used, and the conclusions of the evaluation were as follows. 1) The daylight duct system with multiple light distribution modules of this study included openings within the light distribution modules. The purpose of this method is to make it possible to open the openings of zones in which an influx of natural light was desired in order to let light into the zones. Through this approach, the system improves upon existing daylight duct systems in which light can enter only through fixed locations, thus increasing its efficiency. 2) The daylight duct system with multiple light distribution modules proposed in this study (Case 3) showed up to a 6.1% enhancement of average indoor light intensities compared to a system without light distribution modules (Case 1) and a system with a single light distribution module (Case 2). 3) The daylight duct system with multiple light distribution modules is capable of having the location of its light distribution modules adjusted to increase the uniformity of light distribution indoors. According to the settings of this study, it was found that the system can improve the uniformity of light distribution by 1.0%. In the future, continued efforts should be made to validate additional performance enhancements of the daylight duct system by diversifying indoor and outdoor parameters and the specifications of the daylight duct system, in addition to taking the parameters reviewed in this study into account.

*Keywords*: *Air cap, Blind, Add-in type, Performance evaluation, Prospect right.*

## 1. Introduction

### 1.1. Background and purpose of research

Technological developments related to the conservation of energy have recently become recognized as an important issue in light of global warming and the depletion of fossil fuels, and are considered as a major task to be pursued in current times. According to a report by the US Energy Information Administration, in 2012 the energy consumed by buildings accounted for 47.6% of total energy consumption. This figure, which has been increasing annually, has focused attention on the need to reduce energy consumption in buildings as an important issue that is directly linked to the issue of resolving the energy crisis in general. Of the energy consumed in buildings, the consumption of energy for lighting purposes accounts for a high proportion of the total, at 18% [1]. During the summer season, high solar altitudes result in low levels of natural light induction indoors, leading in turn to high levels of energy consumption for lighting purposes. In light of this, research into building skin modules designed to reduce the consumption of energy for lights in buildings, such as light shelves [2-15], blinds [16-29], louver[30-34], PV[35-37] and awnings [38], has been widely pursued. However, such research, which concerns the means of controlling building skin modules to deal with outdoor environmental factors, has shown rather low levels of efficiency in comparison to the investment required.

A daylight duct is a type of natural lighting system that involves the installation of aluminum applied ducts having a reflectance rate of 98% or higher on rooftops or the top areas of underground floors of buildings to induce the influx of natural light to indoor areas and thus reduce the energy consumed for lighting purposes during the day. Although their scope of application has recently been expanded to include factories, warehouses, residences, and cultural assembly facilities, existing daylight duct technologies that typically involve a single light distribution module have a low level of efficiency due to their ability to induce light only to a certain indoor space, regardless of whether building residents are present or not.

In light of this, this study first developed a daylight duct system with multiple light distribution modules, and then proposed the possibility of establishing an algorithm that determines when the light distribution modules should open. In this way, this study further aimed to

validate the effectiveness of the daylight duct system with multiple light distribution modules using a light environment analysis simulation program.

### 1.2. Methods and Scope of research

This study aimed to develop a daylight duct system with multiple light distribution modules for the purpose of improving lighting performance, and further aimed to validate the effectiveness of the lighting performance enhancements through energy simulations of a light environment. In doing so, the following steps were taken.

The first step was a literature review of the concepts and trends of daylight ducts deemed to be directly related to this study. In addition, performance evaluation methodologies based on light environments were reviewed. The second step was the development of the daylight duct system with multiple light distribution modules, in which methods for opening the light distribution modules of the daylight duct and the associated control algorithms were proposed. The third step involved performance evaluations in which the lighting performance of the daylight duct system with multiple light distribution modules (Case 3) developed in this study was compared with a case without a daylight duct (Case 1) and a case that applied the existing type of daylight duct system with a single light distribution module (Case 2).

The performance evaluation of this study was undertaken using Radiance, a program that is typically used to undertake performance evaluations of light environments [8]. In addition, the performance evaluation was limited to the summer season, a time during which energy consumption levels are high.
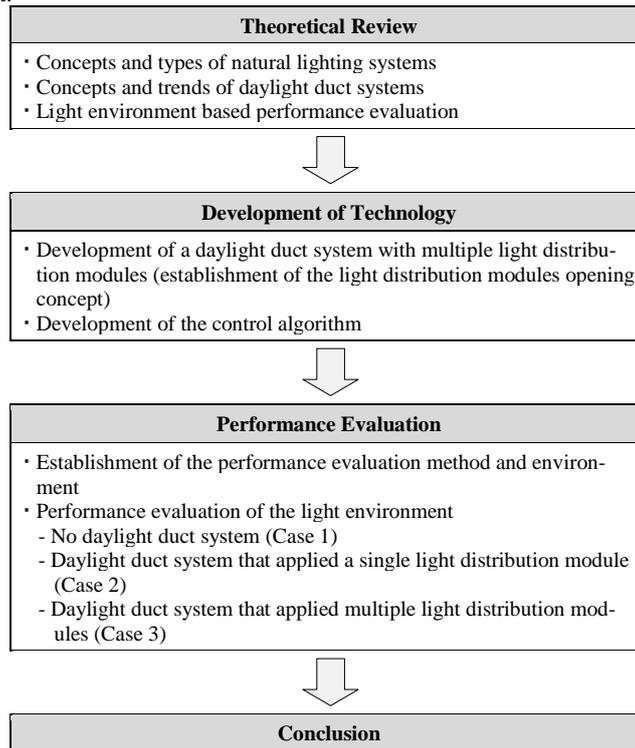
| **Theoretical Review** |
|---|
| ・Concepts and types of natural lighting systems<br>・Concepts and trends of daylight duct systems<br>・Light environment based performance evaluation |

| **Development of Technology** |
|---|
| ・Development of a daylight duct system with multiple light distribution modules (establishment of the light distribution modules opening concept)<br>・Development of the control algorithm |

| **Performance Evaluation** |
|---|
| ・Establishment of the performance evaluation method and environment<br>・Performance evaluation of the light environment<br>  - No daylight duct system (Case 1)<br>  - Daylight duct system that applied a single light distribution module (Case 2)<br>  - Daylight duct system that applied multiple light distribution modules (Case 3) |

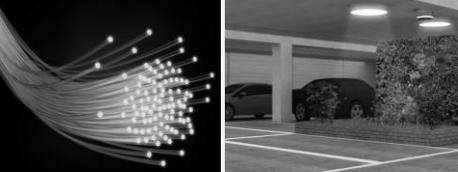| **Conclusion** |
|---|

**Fig. 1:** Research flow chart

## 2. Light Duct Concept and Light Environment Based Energy Performance Evaluation Method

### 2.1. Concept and type of natural light system

A natural lighting system consists of a collection module that collects sunlight, a light transmitting module that transmits the collected light to an indoor space in need of light, and a light distribution module that shines the transmitted light to an indoor space. Reflecting mirrors, light shelves, blinds, louvers, and prism panels are considered natural lighting systems. Natural lighting systems are divided into categories in Table 1.

**Table 1:** Classification and technology of natural light system

| Category | Technology |
|---|---|
| Based on light collecting principle | ・(Reflecting type) Reflecting mirrors, light shelves, induced reflectors, blinds, louvers<br>・(Refracting type) Lenses, prism panels<br>・(Transmitting type) General purpose windows, duct systems<br><br> |

| | |
|---|---|
| |  |
| Based on method of light trans-mission | ・ Spatial transmission, transmission via optical fibers, transmission via daylight duct systems<br> |
| Based on purpose of use | ・ Shading systems, light collecting systems, lighting systems<br> |
| Based on method of operation | ・ Movable type (solar tracking type), fixed type<br> |

Recently, as shown in Table 2, advanced studies have been performed by combining advanced IoT and ICT technologies such as user recognition and occupant location recognition technologies. The level of the technologies will continue to improve, because the operation of these natural lighting systems can contribute not only to improving the indoor light environment by enhancing the lighting efficiency but also to reducing the use of lighting energy. In addition, the application of these technologies has increased, showing a trend of combination with various building element technologies.

**Table 2:** Research trends in natural lighting systems

| Title of study<br>(Year) | Applied to | Applied technology | Natural lighting system operation status |
|---|---|---|---|
| A Study on Light-Shelf System using Location-Awareness Technology for Energy Saving in Residential Space (2014) [39] | Light shelf | Building envelope operational technology based on occupant location-recognition | ○ |
| A Study on Light Shelf System Performance Evaluation Applying User Awareness and Dimming Control in Housing (2014) [40] | Light shelf | Building envelope operational technology based on user recognition | ○ |
| Evaluation of Lighting Performance of Mixed Type Light-shelf in Residential Space According to Angular Variations () [41] | Light shelf | Angle control technology | ○ |
| Development of a Movable Drawer Type Light-Shelf with Adjustable Depth of the Reflector (2016) [42] | Light shelf | Building envelope width ad- | ○ |

| | | justment operational technology | |
|---|---|---|---|
| Automated Blind Control Strategy to Minimize Occupant's Distractions (2013) [43] | Blind | Operational technology considering solar profile angle and occupants | ○ |
| Optimal Control Algorithm Prediction of Venetian Blind in Office Buildings (2017) [44] | Blind | Slat angle control operational technology | ○ |
| The Effects of Automatically Controlled Slat-Type Blind to Reflect Optimum Control Strategies which are Reducing Discomfort-Glare and Improving Energy Performance (2012) [45] | Blind | Slat angle control operational technology | ○ |
| Analysis of Lighting Efficiency According to Repair Works of Sun-tracking controller and glass fiber cable at Glass Fiber Optic Lighting system (2005) [46] | Fiber optic | Operational technology based on solar tracking | ○ |
| A study on the application Methods Characteristics of Daylighting Systems to Building (2008) [47] | solar mirror, Light shelf, Light-pipe | Operational technology based on solar tracking | ○ |

## 2.2. Light duct concept and research trend

A daylight duct system shines sunlight collected through a curved or flat mirror to the desired locations in a building, through a square duct that consists of mirror-like surfaces made of metallic materials with high reflectance rates. The system involves relatively low costs, yet is limited in that it can only shine light to indoor or underground areas over a short distance. The structure of a daylight duct system is as presented in Fig. 2 and Fig. 3, and the systems can be categorized into vertical or horizontal systems. In addition, past research regarding daylight duct systems, as shown in Table 3, indicates that single light distribution module applied structures are capable only of inducing light to specific indoor spaces regardless of whether building residents are present or not, resulting in the problem of lowered efficiency[48].
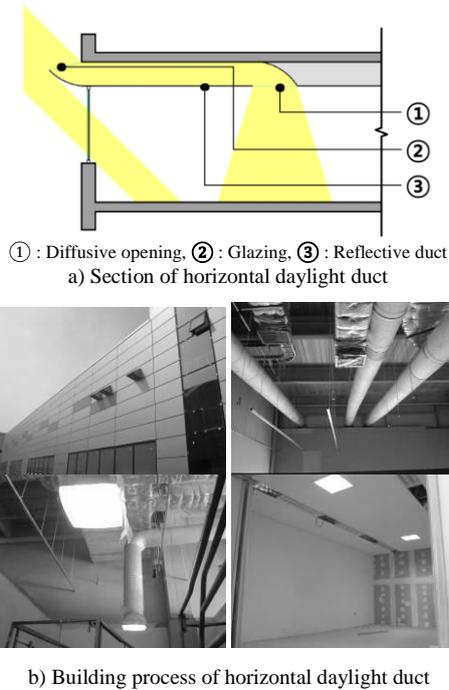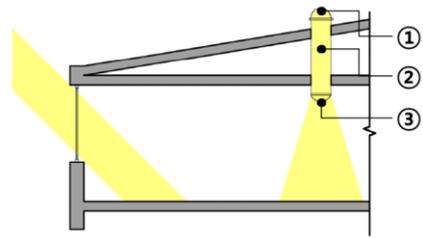


① : Diffusive opening, ② : Glazing, ③ : Reflective duct
a) Section of horizontal daylight duct



b) Building process of horizontal daylight duct

**Fig. 2:** Horizontal daylight duct

① : Diffusive opening, ② : Glazing, ③ : Reflective duct
a) Section of vertical daylight duct



b) Structure of vertical daylight duct

**Fig. 3:** Vertical daylight duct

**Table 3:** Light duct research trend

| Title of study (Year) | Research Goals | Number of light distribution modules in the daylight duct system |
|---|---|---|
| A Study of Light Duct System for Underground Parking Facility (2016) [49] | A performance evaluation of the daylight duct system through a miniaturized model | 1 |
| Developing an Anidolic Ceiling System to Improve Luminous Environment in School Classrooms (2010) [50] | A performance evaluation of the reduction of energy consumed for lighting purposes and improvements to light environments through the application of the daylight duct system to classrooms in schools. | 1 |
| Evaluating Daylighting Performances of Anidolic Light-Duct Systems Using RADIANCE with Photon Map Algorithm in Terms of Light Duct Index (2014) [51] | A lighting performance evaluation through | 1 |

| | | |
|---|---|---|
| | an energy simulation program | |
| A study on lighting Diffusion system of Daylight Duct System (2011) [52] | A performance evaluation of different types of daylight duct systems through real-scale models | 1 |
| An Experimental Study on the Application of Horizontal Daylight Duct System in Building Interior Space (2004) [53] | The establishment of appropriate specifications through performance evaluations of horizontal daylight duct systems | 1 |
| Developing Algorithms to Predict the Luminous Flux Transfer Rates of Vertical Rectangular Daylight Duct Systems with the Consideration of Direct Sunlight Incidence (1996) [54] | Performance Verification of light duct(School facilities) | 1 |
| Prediction of Indoor Visual Environment and Lighting Energy of an Anidolic Light-duct System in Classrooms (2011) [55] | Performance Verification of light duct(School facilities) | 1 |
| The Development of Design Tools of Daylight Duct Systems for Underground Spaces (1997) [56] | Performance Verification of light duct(Underground space) | 1 |

## 2.3. Energy performance evaluation based Light environment

This research proposed a new concept for a daylight duct system, a type of natural lighting system, and accordingly subjected the system to a performance evaluation. In this study, relevant past studies were reviewed with respect to their light environment based lighting performance evaluations, and the results were further applied to pursue studies involving a performance evaluation based on a real-scale testbed [40, 42], a performance evaluation based on a miniaturized model [57], and a performance evaluation based on a simulation program [58]. Although a performance evaluation based on a testbed and miniaturized model is capable of establishing accurate performance evaluation results, the method is limited in that it is not able to take various variables into account. On the other hand, a performance evaluation using a simulation program is capable of reflecting various variables and carrying out analyses from multiple angles. In light of the importance of considering diverse outdoor and indoor environmental variables, this study chose to pursue the method of undertaking the performance evaluation via the use of a simulation program.

**Table 4:** Performance evaluation method types and characteristics

| Sort | Strengths and weaknesses |
|---|---|
| Testbed-based performance evaluation | <br>·Possible to evaluate performance based on the actual environment<br>·Possible to evaluate the precise performance<br>·High cost required to build environment for performance evaluation<br>·Unable to create diverse external environments<br>·Increase of study period when considering external environment factors (external illuminance, temperature, humidity, etc.) |
| Scale model-based performance evaluation | <br>·Lower construction cost compared to testbed-based performance evaluation<br>·Easy to create for diverse internal environments (size and shape of indoor space)<br>·Low precision results compared to full-scale testbed-based performance evaluation |
| Energy simulation-based performance evaluation | <br>·Fewer constraints compared to testbed and scale model when setting the indoor and outdoor environment for energy performance evaluation<br>·Low accuracy of energy performance evaluation results<br>·Simulation analysis tools related to energy and environmental analysis: Radiance, DesignBuilder, Relux, Fluids, ECO2, etc. |

## 2.4. Consideration of Radiance, a light environment based performance evaluation methodology

In this study, Radiance, a software package, was used to evaluate the lighting efficiency performance of the daylight duct. The Radiance software package, developed by Greg Ward Larson of the Lawrence Berkeley National Laboratory (LBL) in the United States, is a lighting rendering and simulation program that has been used by UC Berkeley's Architecture Department in the College of Environmental Design since 1987. Radiance can run properly in a Unix environment on workstation-class computers, and is compiled in C language. Radiance is currently distributed free of charge, and has an active group of users worldwide who discuss usage problems and exchange information and data through the Internet. Furthermore, according to a recent LBL announcement, since December 1, 2002, the Radiance source code has been made available free of charge for commercial as well as research purposes, so that Radiance can become a standard tool for research and development groups and groups performing advanced designs. In addition, Radiance can be used as a plug-in connected to the Web and CAD, as shown in Fig. 4, and is considered suitable for this study as it has the advantage of allowing the light environment to be easily simulated.
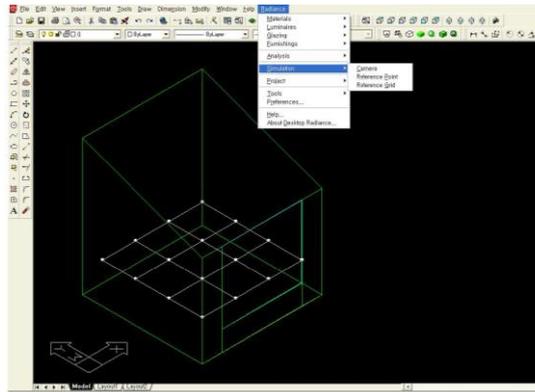
**Fig. 4:** Radiance software execution screen

The Radiance software utilized in this study was configured to set the altitude and azimuth of the sun at various time zones as shown in Fig. 5, in order to perform various light environment analysis. In addition, Radiance is capable of evaluating the performance by accurately reflecting the amount of cloud coverage and the atmospheric turbidity, thus reflecting a variety of external conditions. As shown in Fig. 6, Reflectance, Specularity, Transmittance, and Roughness values are embedded in Radiance to establish various material properties.
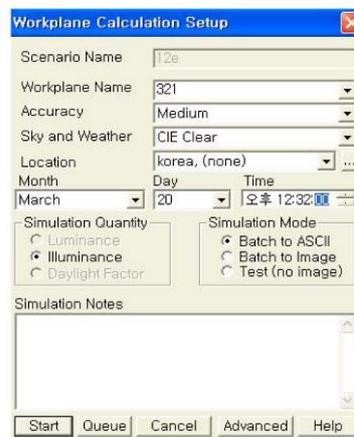


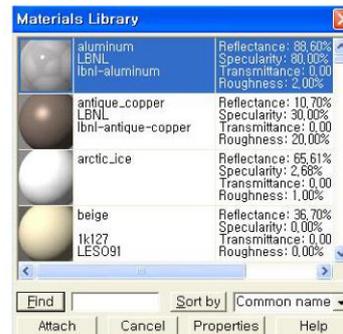**Fig. 5:** Radiance external environment setup



**Fig. 6:** Radiance external environment set up

Radiance has been applied to various studies, as shown in Table 5. In particular, it has proved its effectiveness as a simulation program for indoor and outdoor light environment analysis as well as the light shelf, which is a type of lighting system. In this respect, it is considered a suitable program for the performance evaluation of the daylight duct proposed in this study.

**Table 5:** Research trends based on Radiance

| Title of study (Year) | Evaluation subject | Performance evaluation items |
|---|---|---|
| A Study on the Evaluating Method for Daylight Glare due to Solar Specular Reflection from a High-rise Buildings using the RADIANCE Program (2013) [59] | Solar specular reflection | Glare effect analysis |
| Simulation Study on the Performance Evaluation of Light-shelf focused on the Depth of | Light | Indoor illuminance distribution analysis |

| Space and the Dimensions and Angles of Light-shelf (2013) [58] | shelf | |
|---|---|---|
| Simulation Study on the Performance Evaluation of Light-shelf According to Geometric Shape of Ceiling (2014) [60] | Light shelf | Indoor illuminance distribution analysis |
| A Study on Visual Environment Evaluation of Residential Space Using the Radiance Program (2011) [61] | Venetian Blind | Daylight Factor, Uniformity ratio, Glare |
| The Evaluation of Daylighting Performances in Museum Exhibition Spaces Using Computer Program RADIANCE (2009) [62] | Art museum illumination plan | Indoor illuminance distribution analysis |
| Evaluation of Discomfort Glare Caused by Windows Using RADIANCE Program (2005) [63] | Window discomfort glare | Luminance analysis |
| Analyzing Shading Characteristics of Venetian Blinds Using the RADIANCE Program (2005) [64] | Venetian Blind | Analysis of luminance contrast and uniformity through indoor illumination distribution |

## 3. Development and performance evaluation of Daylight Duct System with Multiple Light Distribution Modules

### 3.1. Development of Daylight Duct System with Multiple Light Distribution Modules

The daylight duct system with multiple light distribution modules proposed in this study and shown in Fig. 7 and Fig. 8 is installed with 2 or more light distribution modules to a horizontal daylight duct. This differentiates the system developed in this study from existing daylight duct systems with a single light distribution module, and enables the system to introduce natural light from outdoors to areas in need of light by opening the light distribution modules as needed. Such daylight duct systems with multiple light distribution modules are deemed to be conveniently applicable to locations in which the usage patterns of indoor spaces are predefined according to a fixed schedule, as can be expected in school buildings. For example, as hallways are rarely used during class hours in school buildings, the installation of light distribution modules of the daylight duct system along the hallways may dramatically reduce the lighting efficiency of the daylight duct system.

On the other hand, if the light distribution modules of the daylight duct system are installed along hallways and in classrooms, and points to be shone with light are designated, lighting efficiency may be enhanced in addition to saving energy for lighting purposes. In addition, the daylight duct system with multiple light distribution modules of this study was proposed to be capable of controlling the opening device of the light distribution module, as shown in Fig. 9.
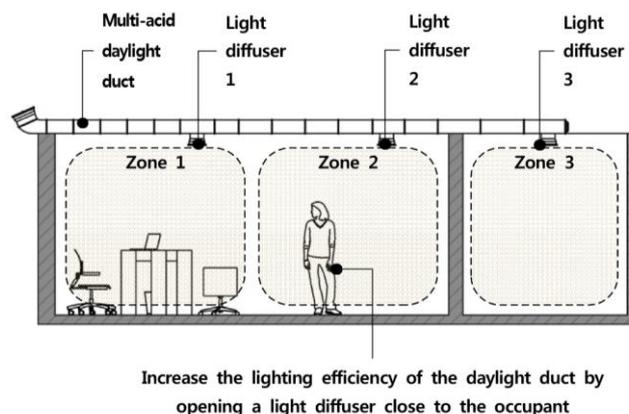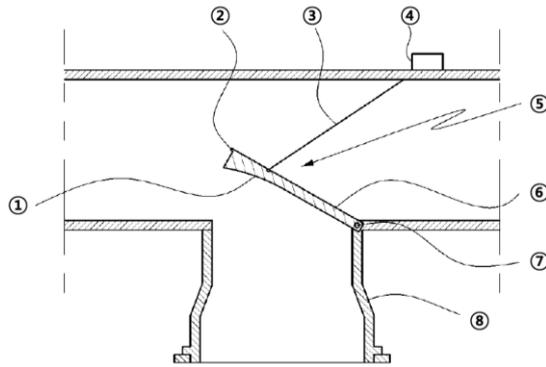


**Fig. 7:** Concept of multi-acid daylight duct system

| ① | Reflective surface | ② | Weight unit |
|---|---|---|---|
| ③ | Wire | ④ | Power unit |
| ⑤ | Means to open and close | ⑥ | Rotating unit |
| ⑦ | Rotating axis | ⑧ | Light distribution unit |

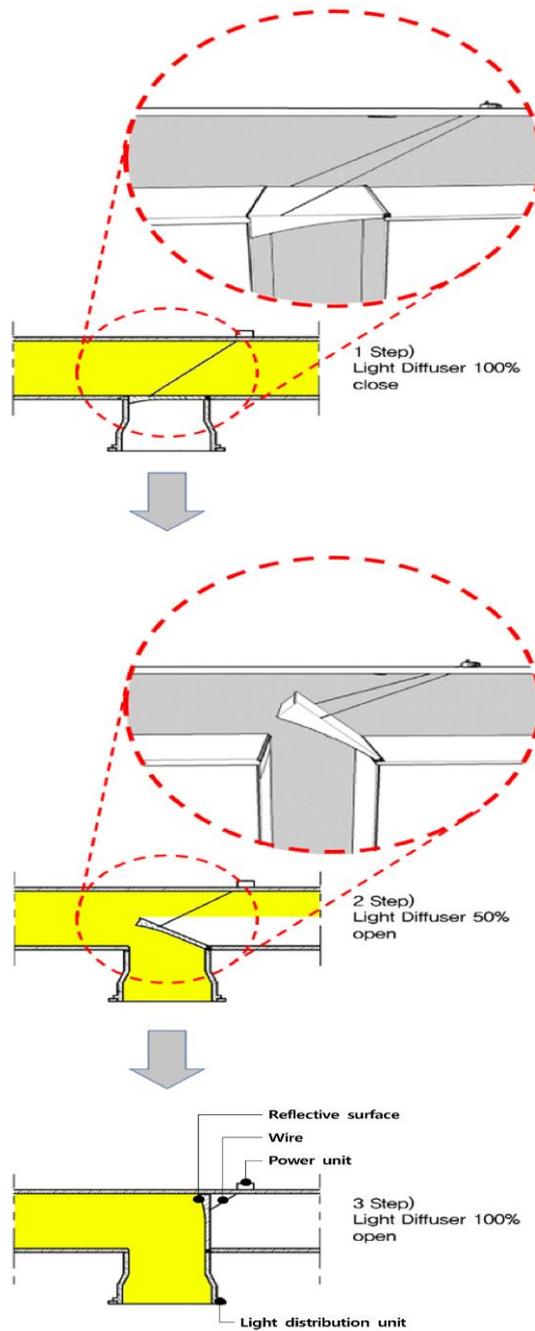**Fig. 8:** Configuration of light diffuser



**Fig. 9:** Daylight duct system diffuser control

The algorithm to control the opening of the light distribution modules of the daylight duct system with multiple light distribution modules considered the presence of building residents and measurements of indoor light intensities, and was designed to introduce natural light from outdoors through the light distribution modules to zones in which building residents were detected. This study, however, did not discuss the method of collecting information on indoor light intensities or the method of detecting the existence of building residents. Follow-up studies regarding these aspects are deemed necessary in the future.
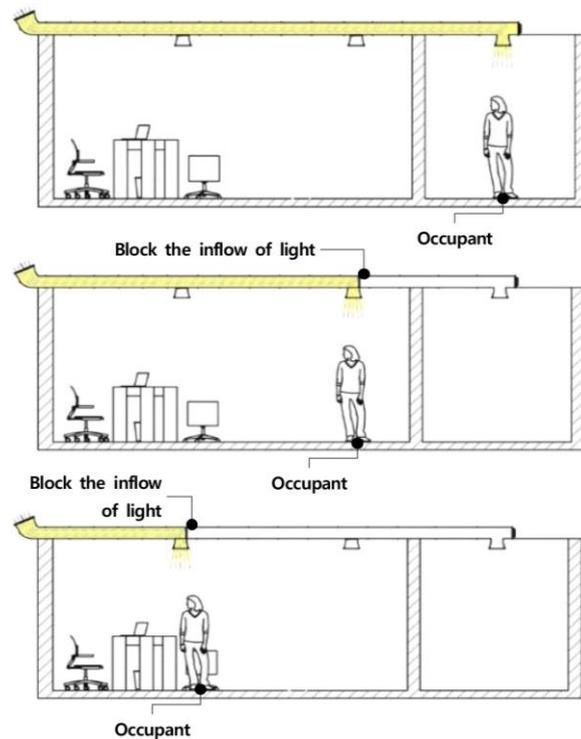


**Fig. 10:** Daylight duct diffuser control according to the location of the occupant

### 3.2. Environmental Setup and Method of the Performance Evaluation

To validate the effectiveness of the daylight duct system with multiple light distribution modules (Case 3) developed in this study, the average indoor light intensity and uniformity of light distribution of an indoor area of the system developed in this study was compared against a case without a daylight duct system (Case 1) and a case with a daylight duct system with a single light distribution module. The environmental setup and evaluation indexes of the performance evaluation were as follows.

First, the indoor space setup for the performance evaluation, as shown in Table 6 and Fig. 4, included an open space that was adjacent to a one-sided hallway in which the size of the room was 6m x 6m at a height of 3m. The width of the hallway was set to 2m. The ratio of the window area of the indoor space facing south and north was 50%, and 5m x 1.8m sized windows were applied. The glass of the windows was set to be clear, non-colored pair glass having a transmittance rate of 80.82%. The reflectance rates of the indoor space were set as 25.10% for the floor, 55% for the walls, and 74.99% for the ceiling.

Second, the geographic location of the building for the performance evaluation was set to the coordinates of the City of Seoul in the Republic of Korea at 127° longitude and 37.5° latitude. The status of the skies was set to the 'very clear sky' setting in Radiance. One noteworthy point was that the lighting performance evaluation of this study was only undertaken facing due south.

Third, to carry out the lighting performance evaluation of this study, the indoor space, as shown in Fig. 11, was divided into 3 zones, in which the light distribution modules were configured to introduce outdoor natural light to Zone 2 and Zone 3. In addition, the cross-section of the daylight duct system with multiple light distribution modules was set to have a width of 400mm and a height of 200mm, and the internal reflectance rate of the daylight duct system was set to 98%.

Fourth, in order to validate the lighting performance in each zone, the minimum indoor light intensity and average light intensity were calculated; based on these calculations, the uniformity of light distribution of the indoor area was calculated. The uniformity of light distribution of the indoor space was calculated without including the light intensity sensor located in the hallway.

**Table 6:** Preferences for performance evaluation

| | |
|---|---|
| Room size | 6.0 m (w) × 6.0 m (D) × 3.0 m (H) |
| Corridor size | 2.0 m (w) × 6.0 m (D) × 3.0 m (H) |
| Reflectivity | · Ceiling : 74.99%<br>· Wall : 55%<br>· Floor : 25.10% |
| Window size | 5.0m(W) × 1.8m(H) |
| Window material | · Type: Pair glass 24 mm (6 + 12 + 6 mm)<br>· Transmissivity: 80.82% |
| Location | Seoul, Korea |

| Sun altitude | 76 (summer) |
| --- | --- |
| Sky and weather | CIE clear |
| Turbidity | 2(Very clear) |
| Directions | South aspect |



a) Space setting for performance evaluation (plan)



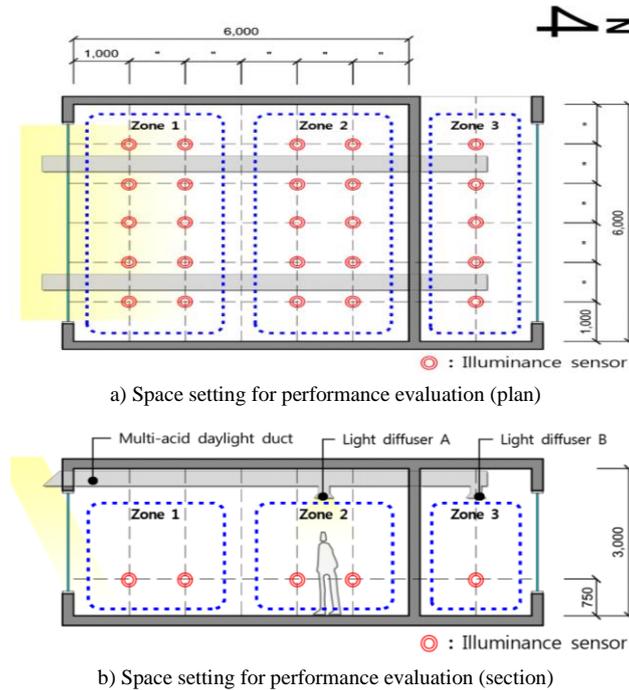b) Space setting for performance evaluation (section)

**Fig. 11:** Space setting and illuminance sensor location for performance evaluation

### 3.3. Performance Evaluation Results

This study undertook a performance evaluation of a light duct system with multiple light distribution modules. The results of the evaluation were as follows.

First, as presented in Table 3, the daylight duct system that applied a single light distribution module (Case 2) presented a 6.1% improvement of indoor lighting performance efficiency compared to the case without a daylight duct system (Case 1) in terms of the average light intensity of Zone 3, where a light distribution module existed. On the other hand, the uniformity of light distribution in indoor spaces for Zone 1 and Zone 2 was slightly lower.

Second, the daylight duct system with multiple light distribution modules proposed in this study can be set to have the openings of its light distribution modules adjusted. The case in which light distribution module A concerning Zone 2 was opened presented improvements of average light intensity of 2.8% and 3.7% and improvements of the uniformity of light distribution of 0.7% and 1.0% compared to the case without a daylight duct system (Case 1) and the case with a daylight system with a single light distribution module (Case 2), respectively. This indicated that the daylight duct system with multiple light distribution modules proposed in this study was effective, and that controlling the openings of the light distribution modules of the daylight duct system upon assessing the presence of building residents would improve the lighting efficiency of the daylight duct system and further contribute to a reduction in the energy consumed for lighting purposes.

**Table 7:** Performance evaluation result (Indoor illumination analysis)

| Case | | Zone | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | | 1 | | 2 | | 3 | |
| | | M.I. (lx) | A.I. (lx) | M.I. (lx) | A.I. (lx) | M.I. (lx) | A.I. (lx) |
| 1 | | 835.1 | 1725.4 | 308.3 | 392.9 | 210.0 | 244.4 |
| 2 | | 827.0 | 1709.0 | 302.3 | 389.0 | 223.5 | 260.0 |
| 3 | Light diffuser A open | 838.9 | 1726.1 | 319.2 | 404.1 | 209.6 | 244.2 |
| | Light diffuser B open | 821.4 | 1700.3 | 301.9 | 385.9 | 222.7 | 258.9 |
| | | | | | | M.I. : Minimum illumination, A.I. : Average illumination | |

**Table 8:** Performance evaluation result (Uniformity ratio)

| Case | | uniformity factor of indoor space |
|---|---|---|
| 1 | | 0.540 |
| 2 | | 0.538 |
| 3 | Light diffuser A open | 0.544 |
| | Light diffuser B open | 0.538 |

## 4. Conclusion

This study proposed a daylight duct system that included two or more light distribution modules to improve upon the lighting efficiencies of existing daylight duct systems, and validated the effectiveness of the proposed system using Radiance, a software program used for light environment simulation and analysis. In doing so, the following conclusions were reached.

First, this study proposed a system in which its light distribution modules can be opened upon assessing the presence of building residents, and further enabled the system to adjust the spatial depth to which light can be introduced. This improved upon the low lighting efficiencies of existing daylight duct systems with single light distribution modules, in which the light distribution module of the daylight duct system was capable of introducing light only to specific spaces.

Second, the daylight duct system with multiple light distribution modules proposed in this study presented up to a 6.1% enhancement of average indoor light intensity compared to a case without light distribution modules (Case 1) and a case with a single light distribution module (Case 2); the system proposed is considered to contribute to a reduction in the energy consumed for lighting purposes.

Third, the daylight duct system with multiple light distribution modules was capable of having the location of its light distribution modules adjusted to improve upon the uniformity of light distribution in indoor spaces, and based on the settings of this study, it was found that the system can improve the uniformity of light distribution by 1.0%.

This study is deemed significant in that it validated the effectiveness of a newly proposed daylight duct system that applied multiple light distribution modules for the purpose of improving upon the performance of existing daylight duct systems. This study, however, is limited, in that it did not consider various specifications as well as the multiple variables associated with indoor and outdoor situations. Follow-up studies in the future should address such limitations to improve the performance of daylight duct systems.

## Acknowledgements

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