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Research Article

A computational approach for achieving optimum daylight inside buildings through automated kinetic shading systems

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Abstract Parametric architecture can be used to improve design quality by integrating and coordinating design components, and any change in one parameter affects the final design. Daylight is a crucial parameter in designing energy-efficient buildings. In this research, daylight inside a building was improved by designing a kinetic shading system with independent units parametrically responding to sunlight through 3D rotation (around the centers of the units) and 2D movement (on the surface of the shading system). Various patterns were determined to create the unit's basic form and allow the designer to have a wide range of options. The units were defined with the plugin "Grasshopper." Their rotation was parametrically controlled on the basis of sun path and weather data by using "Honeybee" and "Ladybug" plugins to provide constant optimized daylighting inside the building. Results showed that the use of such a shading system in optimal situations can greatly increase the efficiency of indoor daylight.

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1. Introduction

Energy consumption has exponentially increased since the industrial revolution and depends on nonrenewable energy sources to a high degree. Living in an era of high technology has provided subtle strategies for utilizing technology and improving the quality of life and sometimes the environment by using renewable energy sources (Taghizade et al., 2019). However, the possibility of whether or not technology use can decrease energy use in buildings by making them self-efficient remains unclear. Illumination is important in the self-efficiency of buildings. This research primarily aims to utilize natural light for illuminating buildings by using contemporary technologies.

This approach is significant because illumination accounts for 15% of the energy consumption of buildings worldwide (Choi et al., 2016). Harvesting daylight is an essential component in the illumination of buildings, and its optimal use can reduce overall energy consumption. Moreover, bringing natural daylight into the indoor environment has a significant effect on the occupants' health and well-being (Nabil and Mardaljevic, 2005; Kirimtat et al., 2016; Wagdy and Fathy, 2015). The absence of daylight can lead to health issues because it informs our biological clocks and body functions (Henriques, 2012).

In previous years, researchers have attempted to decrease dependency on nonrenewable energy sources of lighting by utilizing natural daylight as the main source of lighting for buildings. The majority of these studies have focused on the optimization of daylight inside buildings. However, in their methods, the highest possible efficiency was unachievable due to the limitations of their research methods. In certain approaches, although strategies for daylighting optimization have obtained the best angle of shading units, the system could not be manipulated in three dimensions, thereby reducing the availability and optimum amount of light during the day. In sustainable designs, minimizing energy consumption is the primary objective. Accordingly, windows are utilized to allow sunlight to illuminate the indoor space and reduce energy consumption via electric lighting (Alawadhi, 2018).

Previous research was limited because a methodology for providing optimum interior daylighting still needs further investigation. In the present research, interior daylighting was optimized by designing a kinetic shading system, which was installed on the south façade of the building with a controlled configuration to optimize daylight inside a room. This shading system consisting of independently functioning units not only maximized daylight but also equalized the light level throughout the space while preventing direct daylight on the building. Direct daylight could lead to energy savings by reducing the need for artificial lighting and cooling due to solar heat gain. This research aimed to design a shader, in which the movement and rotation of deployable shading units could be controlled to optimize daylight in the building. The construction cost would be the primary restriction on the immediate implementation of this technology (Parchami Jalal et al., 2019) but could be reduced and likely even overcome through further research and the ongoing improvements in the manufacturing and advancements of technology.

2. Literature review

2.1. Importance of shading devices

In general architectural design, all design aspects and their dimensions, such as location, orientation, form, and lighting, can be regarded as parameters. In conventional architecture, once a design is completed, the entire procedure must be repeated if the designer wants to change a parameter within the design. However, parametric design uses certain software programs, such as Grasshopper, to enhance the design process efficiently by simultaneously integrating and coordinating the design components. A change to any controlling parameter is automatically updated throughout the model (Zargar and Alaghmandan, 2019; Eltaweel and Su, 2017a; Golabchi et al., 2016). Parametric design can be especially useful for designs with constantly changing factors.

Moreover, in dealing with energy consumption issues, people worldwide are confronted with the challenge of decreasing energy consumption while the use of electrical appliances continuously increases (Kirimtat et al., 2016, Jalali et al., 2019). For office buildings, energy consumption from lighting alone accounts for between 20% and 40% of the total energy used (Kirimtat and Krejcar, 2018). The U.S. Energy Information Administration (EIA, 2003) reported that approximately 412 billion kWh of electricity was used for lighting in residential and commercial sectors in the USA alone (Choi et al., 2016). Hence, this issue needs serious attention to be properly addressed.

In some parts of the world, including Europe, the concept of nearly zero energy building (nZEB) must be achieved in new buildings. According to Kirimtat and Krejcar, 2018, the nZEB concept should be adopted in new buildings in the European Union by the end of December 2020. This concept requires the achievement of sustainability measures and is based on performance assessment of factors, such as utilizing daylight and providing visual comfort for inhabitants (Kirimtat and Krejcar, 2018). In recent years, efforts in utilizing daylight as the main source of lighting for buildings have been exerted because of not only energy savings but also benefits to the mental and physical health of building inhabitants. Daylight, as a natural source of lighting, is an essential factor of building illumination, and its optimal use can reduce energy consumption. Moreover, interior daylighting has a significant effect on the occupants' health and well-being, and its absence can lead to negative health consequences (Wagdy and Fathy, 2015). Daylight, whether diffused or direct sunlight, provides significant benefits associated with psychological well-being.

However, potential problems, such as glare or increased cooling loads due to solar heat gain, can also be caused by uncontrolled quantities and quality of daylight. Therefore, various types of shading devices have been designed on the basis of the orientation, location, and glazing types of buildings to increase the thermal and lighting performance

(Bellia et al., 2014). Incoming solar radiation is crucial in the visual and thermal performance and comfort of spaces. Solar shading systems influence the daylight levels of a building and the view to the exterior environment; these systems can also reduce solar heat gain and modify thermal exchanges through the glazed building envelope during the different seasons of the year (Bellia et al., 2014).

2.2. Study objectives

This study introduces a new parametric shading device for sun-oriented envelopes of buildings in four dimensions. On the basis of the literature review, 4D computational shader systems can be designed and developed. Presently, different shader systems have been designed and investigated in the field. The current study focuses on the design of a specialized shader system with independent shading units responding to the sun in four dimensions to improve daylight quality inside buildings and minimize the need for artificial lighting during the day. For daylighting evaluation, several simulation software programs have been developed in the last few decades in various studies (Kirimtat et al., 2016). As the current research focuses on the design of a new 4D shader system to improve the lighting efficiency of a building, simulation modeling is the most appropriate and accurate method to use.

2.3. Previous reviews about designing shader devices for buildings

Previous studies on the design of shader devices indicate that sunlight in task areas can be controlled in the following ways:

- Providing exterior fixed shades that block sunlight for all sun positions;
- Using systems that sufficiently diffuse sunlight to eliminate the potential for glare;
- Providing occupant-controlled adjustable shades (Grondzik and Kwok, 2014).

Studies in recent years have shown a shift in approach from simple and static shader systems to complex ones (Eltaweel and Su, 2017a). During the past 10 years, researchers have further focused on shader devices with two or three dimensions, some of which were parametric with the control variable being the time of day. This shift has occurred because multidimensional systems are designed to respond to additional factors simultaneously and therefore offer enhanced performance characteristics. Moreover, parametric design enables designers to find optimized solutions by isolating various conditions for each parameter in the design. This type of design is used in many disciplines dealing with complex algorithmic relationships, interdisciplinary work, and creative forms. Controlling these operations using conventional tools or imagining them without assistance is difficult because parametric design requires complex operating systems, parametric tools, and specific software. With the assistance of these technological advancements, many applications of parametric design, such as decoration, architecture, urban planning, and structural analysis, exist in many fields (Eltaweel and Su, 2017b).

Accordingly, researchers have focused on designing multidimensional shader systems with variable combinations. This shift has included the design of increasingly nonuniform shader devices and window blinds similar to that of parametric modeling design.

Considering other studies comparable with this research, in the past 10 years, many researchers have investigated the utilization of shaders to provide efficient interior daylighting, some of which used parametric methods. Research has been conducted on Venetian blind and optical louver systems to reflect sunlight into buildings and has produced noteworthy results. However, these results have been limited in their highest optimization to specific hours within a day during specific times of the year. The most likely cause is that these systems are static or manually controlled and incapable of accounting for the changing location of the sun within a day and throughout the year, thereby reducing the uniformity of the reflected light delivered to the interior space and consequently the occupants' visual comfort (Eltaweel and Su, 2017a). McNeil and S. Lee, 2013 evaluated the performance of a passive standard Venetian blind system for a south-facing open plan office space; they optimized daylighting efficiency, discomfort due to glare, and energy savings through reduced lighting. Their results showed that the optical lighting shelf could reduce energy consumption by up to 27% when compared with unshaded windows with standard Venetian blinds. Then, Manzan (2014) demonstrated that the use of a genetic algorithm can be a powerful tool in optimizing the design of a fixed shading device of a south-facing window.

Wagdy and Fathy (2015) investigated the use of a shading system on the exterior façade while examining all combinations of screen parameters, including window-to-wall ratio, louver count, louver tilt angle, screen depth ratio, and screen reflectivity, to obtain optimal interior daylighting solutions. They concluded that the 1:1 depth ratio with downward tilt angles and increasing screen reflectivity enhances the daylighting performance. Mahmoud and Elghazi (2016) evaluated possible rotations and movements for a kinetic shading system on the building façade with hexagonal shader units; their results indicated that the efficiency of shader optimized daylight increases when it only has rotational motions rather than movement. Eltaweel and Su (2017a) optimized daylight by designing a parametric blind, which adjusted the number and rotation of slats to the sun to maximize interior daylighting and prevent direct light penetration (glare) simultaneously; they applied an algorithm through which each slat responded to the sun by receiving direct light and redirecting it to a target point on the ceiling. The density (gap between slats) and rotation of the slats varied depending on the sun's altitude; hence, the light was generally diffused and comfortable for the inhabitants (Eltaweel and Su, 2017a).

Kirimtat et al. (2019) and Zani et al. used computational analysis on a traditional type of static shading system integrated with a single-office façade by performing genetic algorithms in the optimization process; they used daylight and energy simulation engines to evaluate the shading performance further. Their results presented that an effective shading system can be developed and analyzed using parametric modeling techniques combined with computational methods. Another research project focused on light-redirecting fenestration systems that compared two different systems through Radiance's three-phase method (Santos et al., 2018). In this research, Santos et al. (2018) assessed the possible metrics of simplified daylight, which are computationally inexpensive in finding an efficiently mass-produced system. This mass-produced shader system could be integrated into standard office building façades. Then, the authors found an optimized double curvature profile for the proposed louvers with a geometry that redirects incident daylight levels deep into the space. A genetic algorithm was used to produce the high-performance louver curvature. The comparison results showed that optimization based on daylight factor can generate efficient light-redirecting fenestration systems (Santos et al., 2018).

A shaders' design should optimize indoor comfort levels while reducing energy consumption, which leaves us with a multiobjective optimization problem because large sets of interconnected decision variables for optimization are subject to constraints and several objective functions. Currently, all designed shading devices are two dimensional (e.g., XZ) or three dimensional (e.g., XYZ). For certain cases, shader systems are designed to react to the time, sun position, and building location (Eltaweel and Su, 2017a,b). In cases of shader devices considering the time or sun location, the shader itself is two dimensional (e.g., Eltaweel and Su, 2017a). Mahmoud and Elghazi (2016) proposed the only 3D shader that neglects to consider the time or sun location. The proposed 4D shader system improves the efficiency of building lighting and its accuracy by adjusting the shaders into optimized positions on the basis of further active variables.

This research has many advantages that build upon previous research. The 4D system not only moves the shades in three dimensions but also is reactive in real time to incident sunlight. These characteristics allow the shader system to perform precisely. Apart from equally and indirectly (diffused) increasing the illumination of the interior space and preventing the penetration of direct light, the 3D rotation of shading units is a step toward designing complex shading device systems that consider additional real-world factors in real time (Kunwar et al., 2018). The 3D configuration also provides increased flexibility for the shading units that allow them to adapt to incidental sunlight throughout the day and the entire year. This flexibility results in increased interior daylighting for the majority of the day and year rather than only a few specific times in a year and improves efficiency to the built environment. In addition, the capability to apply different patterns for shading units enables designers to customize individual designs to the client's needs. This customizing capability enables additional varieties in the design of something as simple as the variable mechanical system, which is proposed in this study. Hence, the primary goal of this shading system is to optimize interior daylighting while enjoying the aesthetic and functional results beyond the research goals, which are crucial in architectural design. Moreover, the proposed system is installed on the building's façade and needs only a minimal external space to be installed. Table 1 presents the detailed comparison between the present and previous studies.

3. Methodology

The method used in this study can parametrically design kinetic shading units, which can properly and constantly respond to the sun's path and provide optimal interior daylighting. Then, the performance of daylight inside is evaluated. The methodology used for designing this shader system is thoroughly explained as follows. The motivation to use this method for designing kinetic shaders is to create a model that can update and improve the results of interior daylighting simulation by changing the configurations and sizing of shaders. To create the model parametrically, the Grasshopper plugin was used. Grasshopper is a graphical plugin linked to Rhinoceros 3D that aids designers in easily generating parametric forms (Eltaweel and Su, 2017a,b).

The performance optimization involves the optimization of components specific to the generative model of the 4D shading device. First, a virtual room and the geometry of the shading device were created in the parametric modeling environment. The varying parameters of the length, width, and height of the room, the height of the upper window and the top of window, and the dimensions of the shader units were used to calculate the results on the basis of the sun path and the units' pattern (circle and square). Each decision variable had a range of parameters (Noorzai et al., 2015), which correspondingly had an effect on the final geometry of the shading system.

Second, daylight simulation models were provided on the basis of the parametric design of the shading device. Useful daylight illuminance (UDI) was calculated via a daylight simulation engine. Three UDI metrics, namely, achieved ($100 < \text{UDI} < 2k$), exceeded ($\text{UDI} > 2k$), and fell short ($\text{UDI} < 100$), were robust indicators of the actual daylighting provision for an internal space to maximize the achieved UDI in the Galapagos plugin for Grasshopper. The mentioned parameters were considered genomes in Galapagos to optimize the model on the basis of genetic algorithms. Finally, the results were verified through a sensitivity analysis to determine how the different values of a set of independent parameters affect achieved UDI in the building. Fig. 1 shows the specific workflow of this research.

3.1. Geometry definition

The shading system was composed of a flat structure installed on the sun-oriented façade wherein homologous and deployable shading units could move in certain columns and rows. These shading units could also rotate around their own centers. The building and system were parametrically modeled in "Grasshopper," which is a parametric modeling plugin.

Table 1 A comparison between previous related researches and the results of this paper.

Related studies	Research purpose	Research findings	Research weaknesses
González and Fiorito, 2015	parametrically controlling the shadings' geometries	insignificant enhancement of comfort levels and energy efficiency	Esthetics-3D configuration and high efficiency
McNeil and S. Lee, 2013	evaluating the performance of a passive standard Venetian blind system	optical lighting shelf could reduce energy consumption up to 27%.	Research was limited to venetian blinds.
Wagdy and Fathy, 2015	examining all combinations of screen parameters in blinds	Special Configuration increases daylight efficiency	Esthetics-3D configuration and high efficiency
Mahmoud and Elghazi, 2016	possible rotations and movements for kinetic shading system	optimized daylight in certain configurations.	Not a simultaneous rotation/Movement- Merely Hexagons- Not a constant shade inside
Eltaweel and Su, 2017a, 2017b	optimizing daylight with parametric blind	algorithm responding to the sun	Only for blinds/Not a 3D configuration
Zani et al., 2017	Used computational analysis of a traditional type of static shading system integrated to a single office facade by performing genetic algorithms in the optimization process.	An effective shading system could be developed and analyzed using parametric modeling techniques in combination with computational methods.	Static shading device analysis.
Kunwar et al., 2018	reviewing Dynamic Shading in Buildings + different methods of designing	complex shading device types show promise and thus may merit further study and comparison to more conventional shading methods.	
This research	parametrically controlling kinetic system' s Configuration in 4 dimensions based on sun 's path and weather data	4-Dimensional Configuration and movement- Highest possible efficiency- Esthetic- Separate Rotational Logic- Variety in general shape and configuration	Construction Costs

First, the geometry of the virtual room was parametrically modeled before the geometry of shaders could be defined. As shown in Fig. 2, the room dimensions could be defined using any real number with one decimal as follows:

The room's length, width, and height range were 3.0—10.0 m, 3.0—6.0 m, and 3.0—5.0 m, respectively. The window was located on the south (sun-oriented) façade, and similar to other factors, its dimensions and location on the wall were changeable. To prevent any confusion between the lower and top heights of the window for the software and possible program errors, the window's lower height could only be any number from 0 m to 0.18 m. Moreover, the higher height of the window could be any number between the half height of room and the room's total height.

The room was sealed from three other sides, and the light could only penetrate the room through the south window. To simulate daylight, the plugin "Ladybug" for Grasshopper was utilized; full weather information was imported through the weather data files of EPW, which are downloadable online from https://energyplus.net/weather for any specific area around the world (Eltaweel and Su, 2017a,b). As shown in Fig. 3, a surface with a variable gap from the sun-lit façade was defined. This gap could be any real number between 0.1 m and 1.0 m. The shader was then defined on this surface, and its unit configuration (3D rotation and location on the surface) was changeable every hour on the basis of the sun vectors.

Second, a shading system consisting of separate polygonal/circular units was defined on the mentioned surface with a variable gap from the sun-lit façade. The shader

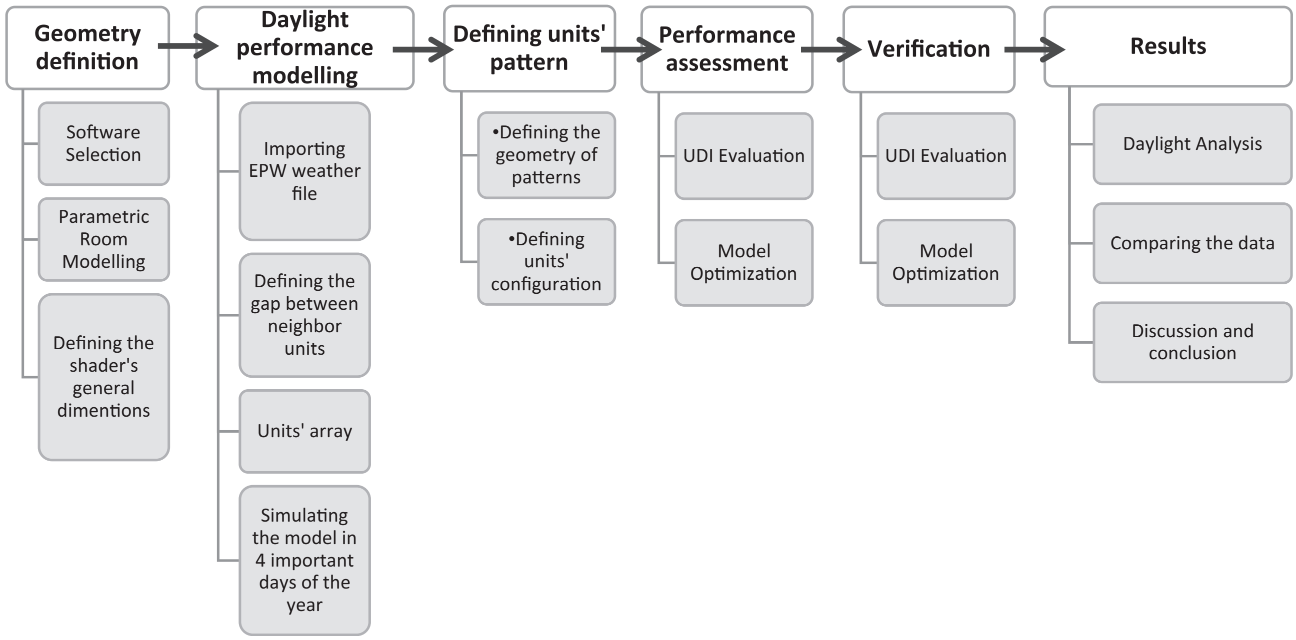


Fig. 1 The work flow specified for the research.

units were defined in specified rows and columns. Center points with 3D rotation capability were then defined for each unit. The dimensions of the units were also changeable. Their radius could be any real number with two decimals between 0.05 m and 0.25 m. Each unit could rotate around its own center in any dimension and move in two dimensions on the surface on which the shader system was installed.

Pattern design: The shading units were all homologous, and their pattern and dimension could be defined by designers and changing from square to circle (which inscribes the square). The general pattern of units is defined in the Grasshopper plugin on the basis of the number of segments defined for them by designers. The shading units performed independently, and as shown in Fig. 3, their rotation and distance from each other could change hourly depending on the sun location.

3.2. Daylight performance modeling based on daylight simulation

The rotation of each unit's surface was configured on the basis of two factors, namely, the incident angle of sunlight and some defined target points on the ceiling. Then, as demonstrated in Fig. 3, each independent unit collected data from the incident light angle and calculated a position to reflect the light to its target on the ceiling. Each unit functioned as the 3D bisector of the sunray vectors and the reflected light (Fig. 4).

The distance between each two neighboring units was demonstrated in Fig. 5 to ensure that the shade of the sun vector at each moment would cast light from the outer side of the upper unit on the inner side of the other unit. Each unit reflected the incident light to a certain target point; hence, the angle between the sun vector and unit was the same as that between the unit and reflection vector given that the radiation and reflection angles are always identical (Fig. 4). Therefore.

$\delta = \delta'$,

$\beta = \Omega - \delta$.

$\theta = \tan -1\ (u/v)$ (computable at every moment).

$2\gamma + \Omega + \theta = 180$ (hence, 2γ is computable at every moment).

$$2\gamma = 180 - [\Omega + \underbrace{(\tan - 1\ (u/v))}_{\theta}] = 180 - 2\,\delta \quad \longrightarrow$$

$$\delta = (\Omega + \theta) / 2 \text{ (computable at every moment)} \quad \longrightarrow$$

$\beta = \Omega - \delta$ (computable at every moment).

where (δ) is the opposing two angles of the unit, (Ω) is the incident angle of the sun, (v) is the distance from the center of the unit to its target point, (u) is the distance from the center of the unit to the ceiling, (θ) is the angle between the reflected light and ceiling, and (β) is the tilt angle of the unit (Fig. 3).

With this mathematical equation, the tilt angle of the virtual surface for each unit on which the unit was placed was determined. Then, the designer could change the general pattern of the units (a circle or any regular polygon with four or more sides).

On the one hand, as demonstrated in Fig. 6, the control logic for distances between adjacent units was calculated such that the sunlight would neither enter the space directly between two units nor be prevented from being reflected to the target points (due to interference from other units). This parameter was important because if the

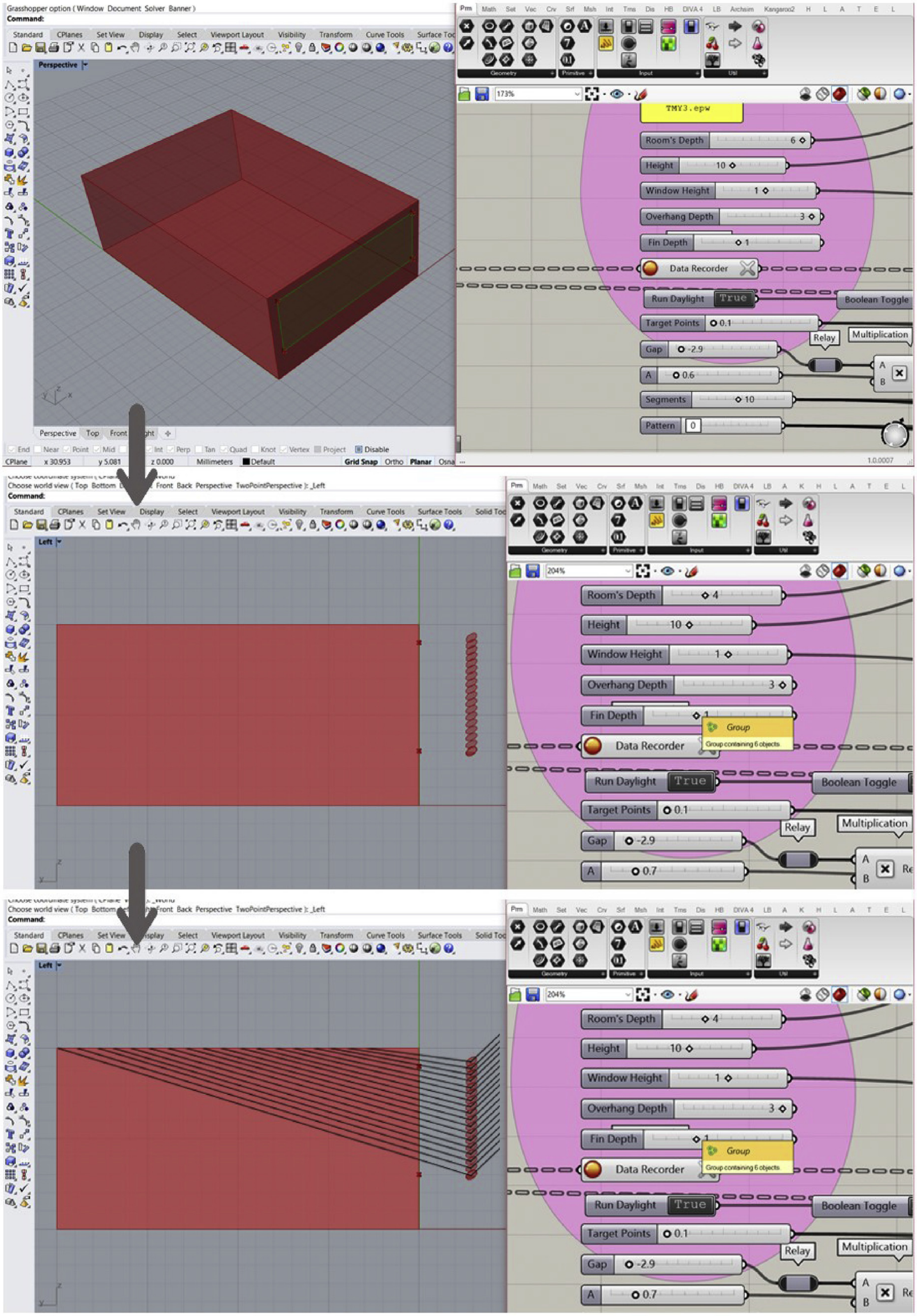


Fig. 2 Stages of geometry definition, from parametric room modelling to defining shader reflection of sunlight toward ceiling.

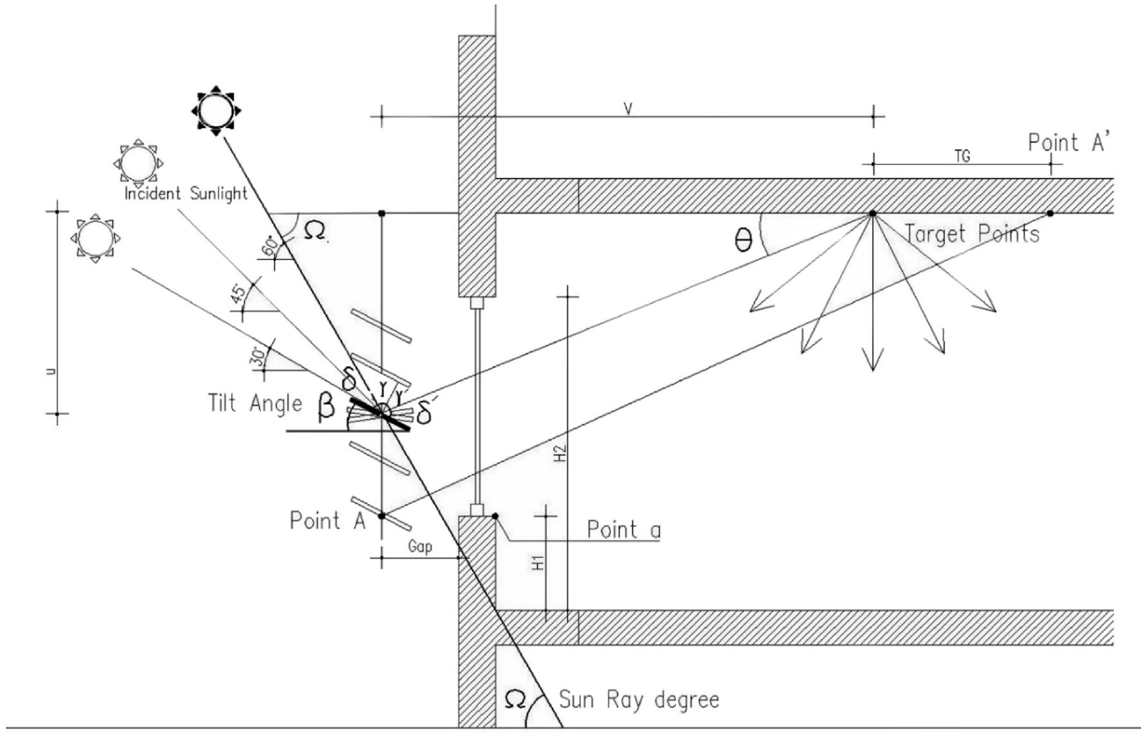


Fig. 3 Dimensions' Definitions, and the Cross-Sectional view of the shading units. As the sun vector was changing constantly, the units were adjusting their configuration to the sun vectors, reflecting the light to the target points.

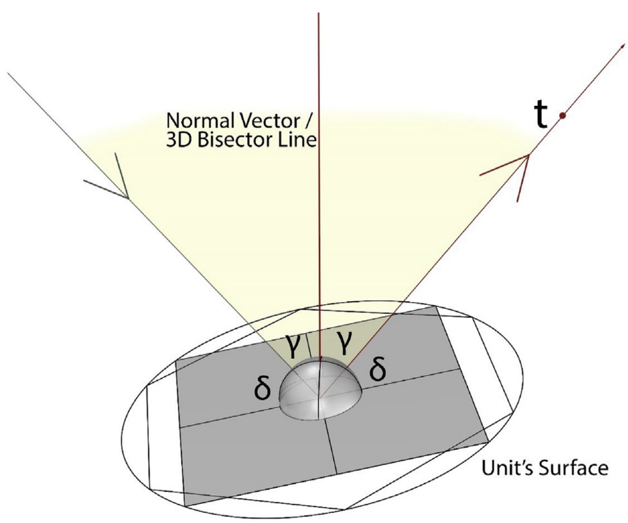


Fig. 4 The angle between the sun vector and a unit was the same as that between the unit and reflection vector since radiation and reflection angles are always identical.

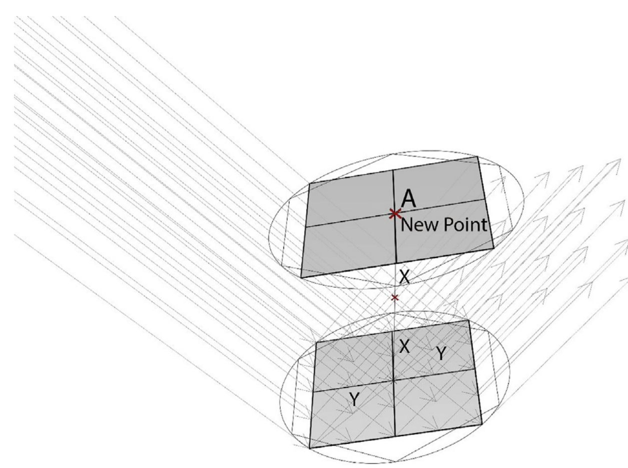


Fig. 5 The distance between each two neighbor units was so that the shade of the sun vector at each moment would cast from outer side of the upper unit on the inner side of the other unit. Supposing the square surface on which the unit would be located, the sun vector was drawn from the inner edge of the bottom square surface (the edge near to the room), and was extended to cross the vertical line passing from point A. Then, the vertical distance between the cross point and point A was measured (x). This height was multiplied by 2 so that center point of the next upper shading unit could be obtained.

distance were too small, then it would completely prevent the penetration of sunlight; however, the amount of light reflected to the ceiling might be reduced. On the other hand, if the distance between the neighboring units was more than appropriate, then it would maximize the reflected light to the ceiling of each individual unit but introduce the risk of direct light penetration (Eltaweel and Su, 2017a).

The distance between the neighboring units was calculated to provide a balance between daylight reflection and direct light prevention (optimal performance). The control

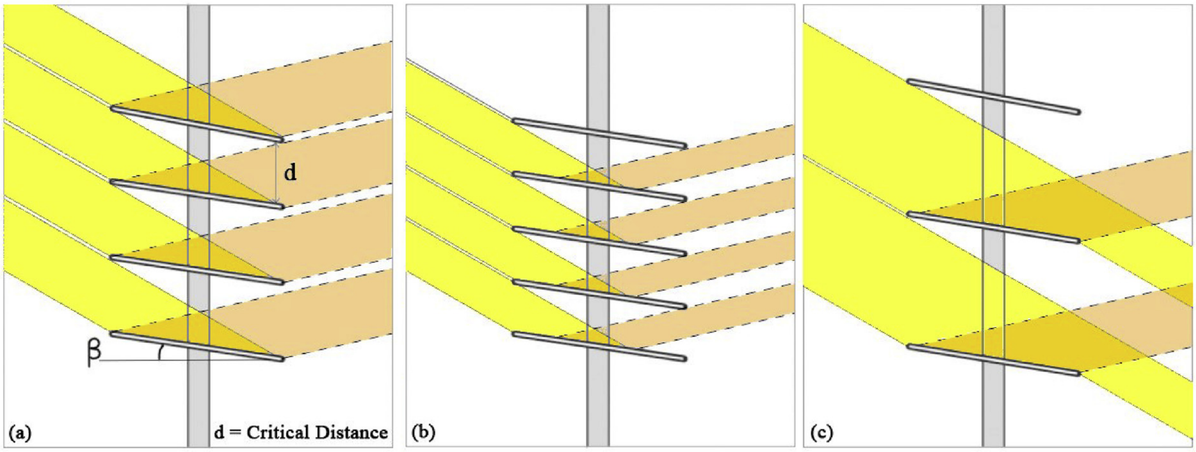


Fig. 6 The control logic of distance between neighboring units was calculated so that in line with the sun's incident angle, units should not overlap each other or have gaps between each other.

logic of distance between the neighboring units was calculated such that, in line with the sun's incident angle, units should ideally not overlap each other or have gaps between each other (Fig. 6). If the distance was low, then the reflection of sunlight was limited (some of sunlight hit the upper surface when reflected), and if the distance was large, then the penetration of sunlight would be possible.

Suppose that the sun vector was drawn from the inner edge of the bottom square surface (the edge near to the room) and extended to cross the vertical line passing from point A on the square surface where the unit is located. Then, the vertical distance between the cross point and point A was measured (x). This height was multiplied by 2 to obtain the center point of the next upper shading unit (Fig. 5).

With this equation, the sun vectors strike the shading units and pass from the outer edge of the upper unit across the inner edge of the previous (bottom) unit. Therefore, the distance between the two units completely prevented the penetration of direct light and provided enough space to ensure that the reflected light could be completely redirected to the ceiling. Eltaweel and Su (2017a) explained this subject in their study. The insignificant difference between rotation angles of units was ignored. Then, the units were placed on the surfaces with the selected patterns.

As previously mentioned, each unit received and reflected the incidental light to its target point on the ceiling. Given that the shading units were glazed and the ceiling was opaque, the target points on the ceiling functioned as the main source of INDIRECT light and diffused this light to the space. In this case study, the shade units were composed of aluminum with 90% reflectivity. Aluminum was the selected material because of its availability in Iran and its suitability of having a good middle ground among its weight, strength, and affordability. Additionally, this material can be polished to achieve different levels of reflectivity. Under a temperature of at least 100 K, aluminum has low solar heat again (Mondolfo, 1976). Hence, with high solar reflectivity, especially in the infrared wavelengths, aluminum shades will have low solar heat again and pass on minimal heat to the supporting structure.

The following reflectance values were used for the interior space in accordance with the EIA handbook: generic floor with 20% reflectivity for the ground, generic wall with 70% reflectivity for the walls, generic ceiling with 80% reflectivity for the ceiling, and generic glazing with 90% transmittance EIA (U.S. Energy Information Administration), 2003.The IES handbook uses these values, as determined by IES, as a generic standard for interior spaces (DiLaura et al., 2011).

3.3. Array logic of the shading units in columns and rows

After defining the geometry and dimensions of units in the Grasshopper plugin on the basis of the location, hour, day, month, room dimensions, target points on the ceiling, and other factors, a point corresponding to h1 (bottom point of the window) with the same height was determined on the structure as the first point for the arrangement of units (A). Point A′ also determined the first target point (A′) at the end of the ceiling. By defining every new point on the structure as the center for a new unit, a new target point was also determined on the ceiling. The distance between target points was changeable and determined on the basis of the depth of the room (TG) (Fig. 3). The procedure was repeated for other units of the column until the shading system was extended enough to ensure that the shadow of its top unit was cast higher than the window's top height.

After defining one column, the columns were arranged next to each other properly. As such, the previous logic was used again to ensure that sun beams were projected from one side of a shading unit to the other side of the lower unit in the previous column. Thus, by considering the incident angle, all rotations/movements of units (distance between units) were computable and changeable at each hour.

To understand the performance of the kinetic shading system further, the configuration of shading units was evaluated on four important days, namely, December 21, June 21, September 21, and March 21. Four identical cases were examined, wherein all room dimensions and shading parameters were the same, except for the time of year.

3.3.1. December 21

The density of the units was more than that of any other day due to the sun angle perpendicular to the wall plane, which prevents the penetration of direct light (the distance between them was the least possible amount). Furthermore, the high density of units reflected a large amount of light to the ceiling. A dense arrangement of units reflected additional thermal energy into the interior space and decreased the need for artificial heating in the space.

3.3.2. March 21 and September 21

The increasingly vertical sunrays caused the larger distance between units than those during winter. However, the shading system was necessary to prevent the penetration of direct light in the sun-lit parts and illuminate the distant parts of the room. Given the increased distance between units, the reflection of light into the room was not caused by unwanted heat increase inside the room.

3.3.3. June 21

Given that the sun's altitude is the highest during this time, the fewer units needed to prevent the penetration of direct light reflected less heat. The increasingly perpendicular sun rays to the wall plane increased the density of the arrangement of units to prevent direct light penetration. The heliotropic response of units to the sun's path was calculated by an angle, which is the bisector line of the sun and reflection vectors.

3.4. Determining the pattern types of the units

The pattern of the units are defined by designers and based on the requirements of different projects. The pattern could either be defined as circles or any regular polygon with four or more sides.

The inscribing circle in which the square was circumscribed was considered the basic pattern, whereas other polygonal patterns were defined by polygons inscribed by the given circle and considered the form of the units. A high percentage of light was expected to be reflected toward the ceiling because if the inscribing circle (which also inscribes other polygons) was divided by the square, then the result would be the square itself and four exceeding sectors. Thus, for circularly shaped units and other polygons, a sun vector was projected from one sector of the top unit to the front sector of the previous bottom unit. This behavior indicated that each pair of units overlapped with each other on one sector and their other points reflected the light inside the room. Hence, a circle and other polygons could be defined as the pattern of the units.

As a short review of the methodology, every unit should reflect the light to a specific target point on the ceiling. The target points, which had a certain distance from each other, illuminated the room by equally and constantly diffusing daylight to all parts of the room. Moreover, the interior portions of the room were illuminated while preventing the extra glare in the parts near the window. The ceiling functioned as the main source of indirect light by distributing the light to the interior space.

3.5. Performance assessment of the shading system based on various factors

The daylighting adequacy in this stage verified that the room with the shading system had sufficient daylight during the occupied hours for the entire year. For precise analysis, the "Honeybee" plugin for Grasshopper was applied in cooperation with another plugin called "Ladybug." Ladybug and Honeybee are two open-source plugins for Grasshopper and Rhinoceros that help in exploring and evaluating the environmental performance of the system.

Ladybug imports the standard EnergyPlus Weather (.EPW) files into Grasshopper and provides various 3D interactive graphics to support the decision-making process at the initial stages of the design. Honeybee connects the visual programming environment of Grasshopper to four validated simulation engines, namely, EnergyPlus, Radiance, Daysim, and Open Studio, which evaluate the building energy consumption, comfort, and daylighting. These plugins enable a dynamic coupling between the flexible and component-based visual programming interface of Grasshopper and the validated environmental data sets and simulation engines (Sadeghipour and Pak, 2013).

First, related weather data and the sun's path in a specific location and time were gathered by importing the EPW file of that zone. After the units adapted their configuration on the basis of related EPW data, the simulation data of interior daylighting was obtained through a process performed in the Honeybee and Ladybug plugins. In this study, the daylighting criteria for evaluation were based on UDI, which is defined as the fraction of the time in a year when the illuminance of indoor horizontal daylight at a given point falls in a given range (Carlucci et al., 2015). The following UDI metrics are proposed: achieved ($100 < \text{UDI} < 2\text{k}$), exceeded ($\text{UDI} > 2\text{k}$), and fell short ($\text{UDI} < 100$). These metrics are robust indicators of the actual daylighting provision for an internal space. The main purpose of the UDI scheme is to allow the ready comparison of multiple design options on the basis of their daylighting performance (Nabil and Mardaljevic, 2005), wherein the achieved UDI is defined as the annual occurrence of illuminances across the work plane within a range considered "useful" by the occupants (Mardaljevic et al., 2012).

The upper, lower, and intermediate categories represent the percentage of time when an oversupply of daylight might lead to visual discomfort, insufficient daylight exists, and an optimal range of the illuminance level is available, respectively.

Accordingly, the authors used the analysis type "annual daylight simulation" to obtain the daylight performance in terms of UDI. The performance of the shader was measured under different conditions. Finally, the model was optimized using the "Galapagos" plugin to maximize the desirable UDI (between 100 and 2000).

4. Standard sample case study

This study was applied to a virtual project in Tehran as the sample city because the sky is clear most of the year and its rainy/cloudy weather is not an interfering variable. Additionally, the maximum use of light was crucial and required the project to be localized somewhere that direct daylight was available on most days, thereby causing over-lit situations in an office room on the seventh floor of an eight-story building. The south façade was oriented toward the sun. The absence of an external barrier cast a shadow inside the room, except the shading system, when installed. The gap between the shader and façade and the unit patterns are changeable. The work hours for this building were from 9:00 a.m. to 5:00 p.m.

To improve the performance of the shader device further, an optimization with "Galapagos" for Grasshopper was performed on the model to obtain the best solutions and all the varying parameters were reoptimized. The performance of the shader system improved by finding the best cases, and the shader provided the most effective daylighting performance in the entire year. The model's different varying parameters were improved with the Galapagos plugin, which provided the highest desirable UDI between 100 and 2000 and identified the cases where the performance of the shading system was maximized. As shown in Fig. 7, the researchers intended to find the best room dimensions, the window area, the window position on the south wall, the radius of the shading units, and the best pattern for the units such that the achieved UDI was the highest value in the optimization. "Galapagos" for Grasshopper was used to optimize the varying parameters. This plugin utilizes a genetic algorithm for displaying the optimal answers of the designer (Zargar and Alaghmandan, 2019). Optimization ran for 36 h, and all CPUs of the PC were utilized and provided 17 evaluated generations of genomes in sequence. The highest efficiency in the performance of the system was 83.24% for the desirable UDI (between 100 and 2000).

5. Results analysis

5.1. Daylighting evaluation (UDI) in the optimized cases

This section explains the daylight simulation results with the kinetic shading system under different cases. The room's depth, height, and window size were changed, and the results indicated their effects on the daylight performance of the building. The genetic algorithm optimization "Galapagos" for Grasshopper was used to evaluate the results and determine the best solutions. Galapagos attempted to reach a minimum acceptable solution for each spectator in different conditions (Zargar and Alaghmandan, 2019). Moreover, this newly developed Grasshopper optimization plugin allows architects to perform interactive structural optimization of highly sophisticated models efficiently and rapidly on a single platform (Wonoto and Blouin, 2019). As previously mentioned, the achieved UDI (100 < UDI < 2k) was defined as the objective function of the Galapagos plugin, and the model was run until it reached the 17th generation of achieved UDI optimization. Fig. 7 displays the optimization results.

In the first generation, the results showed that the lower and top heights of window were 0.08 and 1.65 m, respectively. This finding indicated that the best location for the window's lower and top heights would be a number between these two numbers to maximize the shader's daylight reflection into the interior space. As a result, the reflected light could go further and reach to a deep part of the room, and the target points could also be located

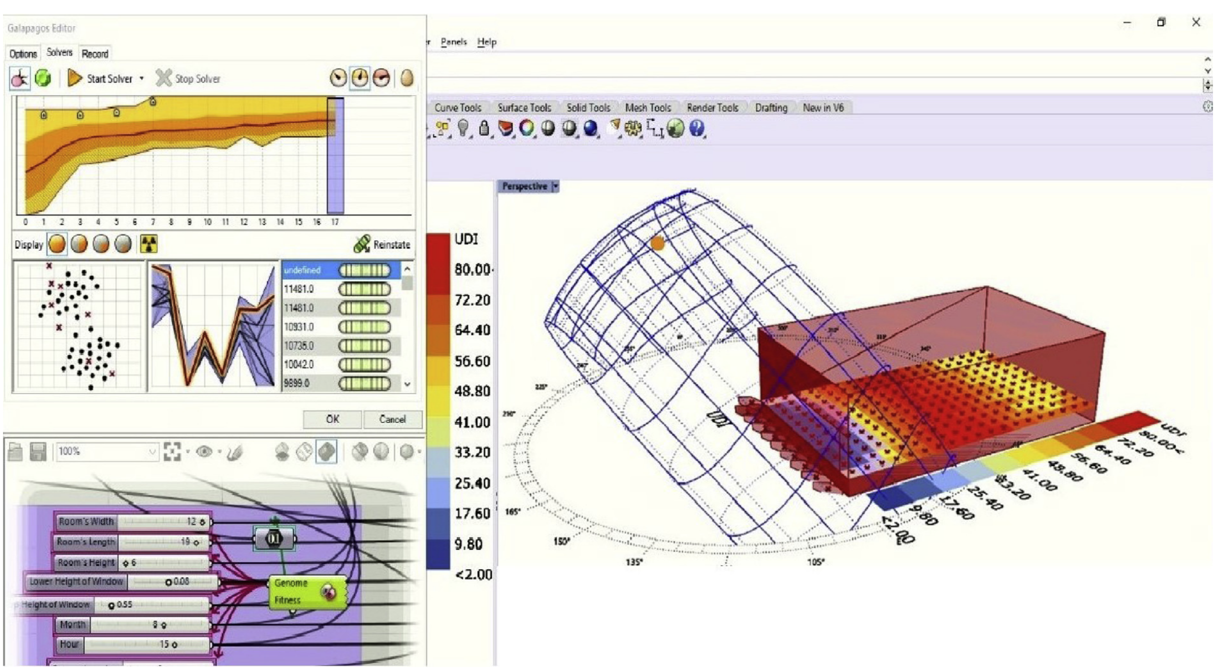


Fig. 7 Optimization of the model based on UDI with using "Galapagos" optimization component.

further from the window. To prevent potential glare, it was supposed to increase the lower height of the window first to at least 1.7 m height from the floor; however, this solution would prevent enough reflected light to enter into the building, especially when the room's depth was 3 m. Thus, to increase the optimum daylight inside the building, the room's height should be more than 3 m. However, this solution is not economical. Therefore, the best solution seemed to utilize the interior design for the prevention of potential glare (e.g., increasing the distance between the office desks and the window).

In the next step, by evaluating the room's dimensions, the best dimensions obtained for the room were 3 m, 9.5 m, and 6 m in height, depth, and width, respectively. These numbers indicated that it was unnecessary to increase the room's height to achieve an increased UDI inside the building. If the room's height is increased, then the height and the area of window must also be increased. However, the beam light generally decreases in efficiency as it covers long distances. To prevent this problem, the room's depth should be decreased. By evaluating the optimized depth of the room, which was directly correlated with the window location, this number was close to the best room depth achieved in the optimization because the window location and the rotation angle for the shader units let the light beam cover a long distance and maximize daylight inside the building. The evaluation of the room's width showed that 6 m could be the maximum depth in the optimization. Furthermore, the increased room depth increases the daylight gain inside the building.

Then, the pattern of shader units was evaluated. The optimized pattern of the shader units was a hexagon. The configuration of units ensures that the gap between them would be the least to prevent overlapping. The reduction of the gap between units with the square pattern increases the overlapping in the corners. The results showed that hexagonal units would best cover this gap and therefore could be used as the optimized pattern for the shader units.

The final findings showed that the use of shading units on the sun-lit façade improved the quality and quantity of daylight in the room. Therefore, minimal artificial light would be needed in using such system for standard office or educational buildings. The proposed system improved the quality of light in the building and decreased the need for lighting with electrical energy.

6. Sensitivity analysis

Sensitivity analysis was applied to the optimization results to validate the model. Given that test grids were located on a surface parallel to the floor (Fig. 8), the increase in UDI was directly correlated to the increasing depth and width of the room. Fig. 8 shows that the optimized solution has a depth of 9.5 m, which was close to that of the maximum length of the room. Moreover, the room width of 6 m was also the maximum width of room. The optimum height was 3 m in most of the results. Regarding the room's high depth to increase the achieved UDI, the room's height must be the least possible amount to allow the reflected light to cover long distances inside the room and reach to the end of the ceiling. Moreover, the lower height of the window was slightly higher than that of the floor, and the top height of the window was also slightly higher than the top half height of the room. This finding was directly dependent on the location of target points on the ceiling. The low height of the window increases the location of depth target points on the ceiling.

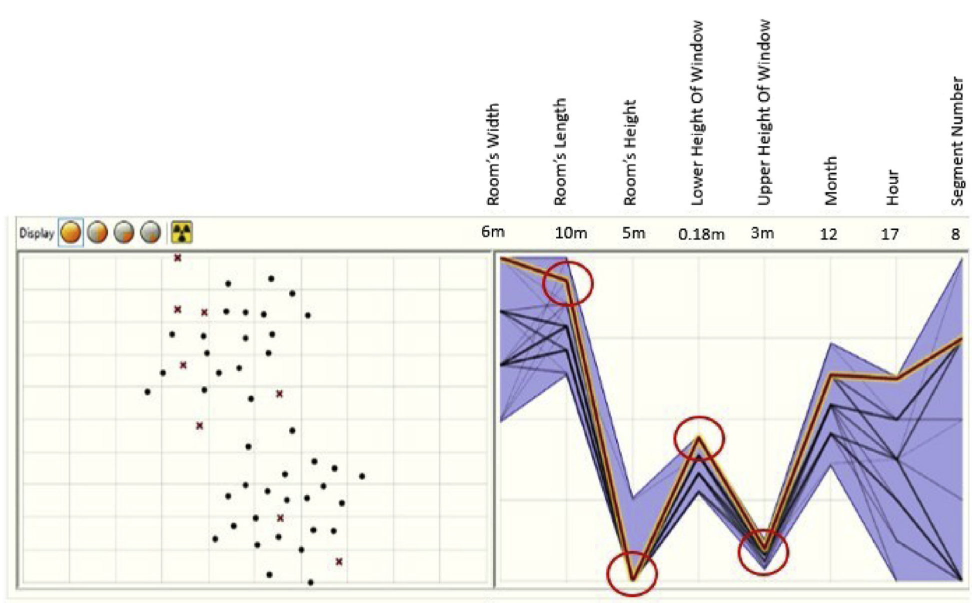
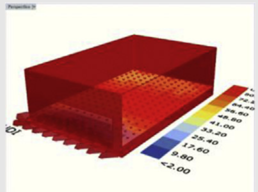
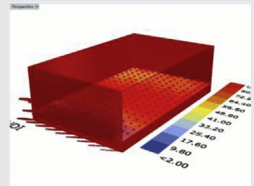
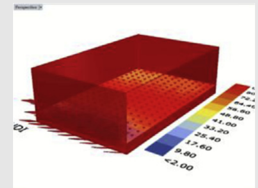


Fig. 8 Parameters range and optimized answers with using "Galapagos".

Table 2 Comparison of the parameters of the top three solutions having the same UDI.

	Case 1	Case 2	Case 3
			
Room's Width	6 m	6 m	6 m
Room's Length	9.5 m	9.5 m	9.5 m
Room's Height	3 m	3 m	3 m
Lower Height Of Window	0.08 m	0.08 m	0.08 m
Top Height Of Window	1.65 m	1.65 m	1.65 m
Month	8	8	8
Hour	13	13	13
Segment Number	6	6	4

To obtain the best option of optimization, the top three optimized solutions resulting in the same amount for the achieved UDI were compared in Table 2. In all these three cases, the room's height, depth, and width and the lower and top height of the window were the same. In the first and second cases, the only difference was the hour when the room was best optimized. In both cases, the hexagon was the best pattern for optimization. However, the second and third cases obtained different results. The hexagonal pattern was the best answer in the second case, whereas the square was the optimized pattern for the third case. The comparison of these results showed that an insignificant difference existed between the square and hexagonal patterns. Therefore, both patterns could provide the most optimized daylight inside the building. However, the units with the hexagonal pattern could further adapt themselves to the sun's movement and sun vectors during different hours of the day.

7. Discussion

When no shading system was installed in the control scenario, the direct light in the outer portion of the room was generally high, and the lack of shade could be uncomfortable for the occupants as the inner portions of the room were dim. In the test scenarios, with the shading units arranged and their orientation/distance determined by the sun's path, the natural interior daylighting performance improved at all points throughout the year although the exact results vary in the entire year. Diffused daylighting was distributed equally inside the room with low glare and over-illumination at the outer portions of the room, and bright and dependable light levels were introduced into the interior portions of the room to provide an appropriately illuminated space for the entire room.

The results of this research can be used in the design of shading systems of sun-lit façades to decrease the need for artificial lighting and increase the self-efficiency of built environments by providing natural interior daylighting during the day. The proposed shader diminished the need for artificial lighting even to zero during daytime, especially for projects with standard room dimensions. For large projects with complex or expansive interiors, the system could increase the natural interior daylighting to near-minimum standard through the use of exterior wall fenestration alone. The authors believe that this system can achieve significant success when applied to office and educational buildings with work hours during day and make them self-efficient by providing interior lighting. This study could be a crucial step toward decreasing building energy consumption while increasing the wellness of inhabitants through the introduction of vital natural daylight into the built interior environment in a responsible and efficient way.

8. Conclusions

In this study, a kinetic shading system was proposed to adjust various shading unit parameters, such as rotation, spacing, and distance from the building façade, on the basis of real-time changes in the local environmental situation and sun path and the delivery of real-time results. Shading units were controlled parametrically and responded to the sun heliotropically on the basis of a preprogrammed sun path and then reflected the light to selected target points inside the room. The target points then diffused the light into the interior space and improved its quality and quantity.

The experiment was tested in terms of the changes in UDI, and significant improvements were observed. Compared with a previous research, the recommended shading system demonstrated many advantages, including the capabilities to increase illumination inside the room and improve the quality and equality of daylight. In this method, the ambient (diffused) light was maximized and the possibility of glare was reduced.

Among its advantages, the 4D configuration of the shader system was the most important one that enabled it to have very precise and efficient adjustments based on sun position in the sky. Each unit of the system had an independent configuration based on the sun position and its target point on the ceiling that further improved the preciseness of system performance. The units could be any polygon with four or more sides. The shade shape variety, 3D rotation, and 4D performance provided limitless possibilities, which are important in the architectural design of shaders by providing the appropriate aesthetics and functions in their designs. Controlling the shading system based on the environmental conditions contributed to the goal of creating intelligent building equipment.

The construction cost was the primary restriction for the immediate implementation of this technology but could be reduced and likely even overcome by conducting further research on the existing improvements in manufacturing and advancements in technology. Finally, the proposed system can contribute to the field of automation in construction.

9. Future directions

The design of such shading systems for buildings with complex forms is recommended by the authors. A future investigation can focus on the means for developing such shading systems for curved façades to utilize sunlight as the main source of lighting for buildings. Through the kinetic shading of façades with free forms and a similar methodology, the units should be able to rotate and move in three dimensions.

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