RESEARCH ARTICLE Journal of Daylighting 11 (2024) 55-68 doi:10.15627/jd.2024.4

ISSN 2383-8701

Journal of Daylighting

Journal homepage: https://solarlits.com/jd

A Multi-objective Optimization of Window and Light Shelf Design in Office Buildings to Improve Occupants' Thermal and Visual Comfort

Fatemeh Rezaei,[*,a] Hamed Sangin,[b] Milad Heiranipour,[c] Shady Attia[d]

[a] *Faculty of Architecture, KHATAM University, Iran*

[b] *Department of Architecture, Faculty of Architecture and Urbanism, University of Art, Tehran, Iran*

[c] *Department of Energy, Politecnico di Torino, Turin, Italy*

[d] *Sustainable Building Design Lab, Department of UEE, Faculty of Applied Sciences, University of Liege, 4000 Liege, Belgium*

Article info

Article history:
Received 29 March 2024
Revised 6 April 2024
Accepted 13 April 2024
Published online 28 April 2024

Keywords:
Light shelf
Window design
Occupants' comfort
Office buildings

Abstract

In office buildings, an efficient design of windows and using light shelves as a passive design strategy significantly influence the thermal and visual comfort of occupants while enhancing the productivity and health of users. This study proposes a multi-objective optimization for the optimal design of windows and light shelves in office buildings to improve occupants' comfort. Initially, a parametric model was developed using Grasshopper parametric software. Afterward, the Honeybee energy and daylight plugin was employed for simulating thermal and visual conditions, and finally, multi-objective optimization was conducted with the Octopus plugin. This plugin can determine the best solution as a compromise decision for maximizing occupants' comfort. In this paper, an office building in Tehran has been chosen as a case study. The decision variables are window-to-wall ratio (WWR), shading control strategy, viewpoint, the transmission of glass, light shelf length, and light shelf height. The objective functions of the study are the annual average Predicted Percentage of Dissatisfied (PPD) and the annual average Discomfort Glare Probability (DGP). According to the results, the proposed optimization model leads to an 18.5–70.1% and 9.3–57.1% reduction in DGP and PPD indexes, respectively. The study findings provide practical and useful instruction for architects to select optimal specifications of windows and light shelves to develop occupants' thermal and visual comfort in office buildings.

1. Introduction

About 40% of the world's total primary energy is consumed in the building sectors [1]. With the improvement of the people's daily needs and the population growth, the energy usage of the building will continue in the future. In addition, according to a 2019 Asian study, CO2 emissions could double by 2030 if energy savings issues are ignored [2]. Unfortunately, according to the latest reports published by the World Statistical Yearbook in 2021, total primary energy consumption in Iran has increased significantly, from 5.91 BTU (British thermal unit) in 2002 to 12.05 BTU in 2021, which means a change of 103.9% between two decades. In other words, Iran's greenhouse gas emissions, electricity, and natural gas consumption increased by 144.9%, 290.3%, and 332.9%, respectively, between 2002 and 2021 [3]. Windows and sun shading systems impact building energy saving since they are one of the most energy-absorbed parts of the buildings' façade [4], [5]. The window is a transparent element in the building envelope that directs visible sunlight to the interior space, decreases lighting energy usage, and is heated by solar energy in winter. So, they help reduce thermal energy consumption and even improve the occupants' visual comfort [6]. Since establishing window systems is done in the early design stage, applying changes in the future is not easy. Generally, the initial design stage is the most important step in building design because about 80% of the building costs are related to this stage [7-9].

Occupants' productivity in office buildings directly impacts the organization's financial efficiency and overall growth [10]. At the same time, the minimum possible energy should be used in these

*Corresponding author.
f.rezaei1@khatam.ac.ir (F. Rezaei)
hamed.sangin@gmail.com (H. Sangin)
milad.heiranipour@polito.it (M. Heiranipour)
shady.attia@uliege.be (S. Attia)

buildings [11,12]. Previous research has confirmed that a major part of the energy consumption in an office belongs to window heat loss and cooling needs due to solar radiation [13]. Window design is a complicated multi-objective problem since solar energy absorption through windows affects occupants' comfort and building energy consumption in summer and winter [6]. The optimal design of the window alone cannot play a significant role in improving the occupants' comfort, so advanced daylight control systems with a more uniform distribution of light in the space can help provide comfort in the building and reduce energy consumption [14]. A light shelf is among these systems. Using light shelves as a passive design strategy can help enhance occupants' thermal and visual comfort while improving the health, efficiency, and lifestyle of buildings' users of buildings [15].

The design of windows and light shelves involves several important factors that influence redirecting natural light into the space. Maximizing natural light is crucial in window and light shelf design [16]. The placement, size, and orientation of windows should be optimized to allow ample daylight to enter the space. The placement, size, and orientation of windows help reduce the need for artificial lighting and create a more comfortable and visually appealing environment. While daylight is desirable, excessive solar heat gain can lead to discomfort and increased cooling loads [17]. Designing windows and light shelves to effectively regulate solar heat gain is crucial. This can be accomplished by utilizing shading devices, low-emissivity coatings, or glazing materials with suitable solar heat gain coefficients. When developing a light shelf system, key considerations include the depth, material selection, and angle to optimize its functionality [18]. The influential design parameters of the window and light shelf system are illustrated in Fig. 1.

It is vital to consider shading control strategies, however, there is a lack of research that systematically assesses the effects of these strategies on the overall comfort of occupants when it comes to measuring the effectiveness of light shelves [18-21]. So, more precise research should be carried out to determine the effect of appropriate control strategy on light shelf design to develop occupants' comfort. Considering the reviewed literature, much research has been done on using light shelves or optimal window design in buildings to improve user visual comfort and save energy [15,17,22-24]. In addition, little research has been conducted on combining optimal design parameters for window and light shelf systems to enhance occupants' thermal and visual comfort. Upon reviewing existing research, a notable gap in the literature emerged concerning the need for a novel approach that optimizes design by simultaneously addressing multiple objectives and achieving an ideal equilibrium between thermal and visual comfort. Hence, this study aims to propose a multi-objective optimization design of window and light shelves to enhance occupants' comfort in office buildings.

At first, a base case was modeled with Grasshopper 1.0.0007 version in the Rhino 6 (SR16), and visual and thermal analysis was performed with the assistance of the Honeybee and Ladybug plugins version of 0.0.66 [25]. Then, by combining the considered design variables, 7500 cases were obtained, and the results were then imported to the Octopus plugin to perform the optimization process and assess the answers. All simulations were performed annually and for the location of the Tehran Weather Station in Iran. In this context, a need was identified to propose a multi-objective optimization design for window and light shelves to enhance occupants' comfort in office buildings. The objective of this study is an attempt to respond to the following questions:

- How can multi-objective optimization techniques be applied to the design of windows and light shelves to simultaneously enhance thermal and visual comfort in office buildings?
- What are the key design factors and strategies that contribute to achieving the overall best solutions in designing windows and light shelves for improved thermal and visual comfort in office buildings?
- How does the integration of window and light shelf design impact the improvement of occupants' thermal and visual comfort in office buildings?

The research seeks to enhance the current knowledge base by exploring how the integrated design of windows and light shelves

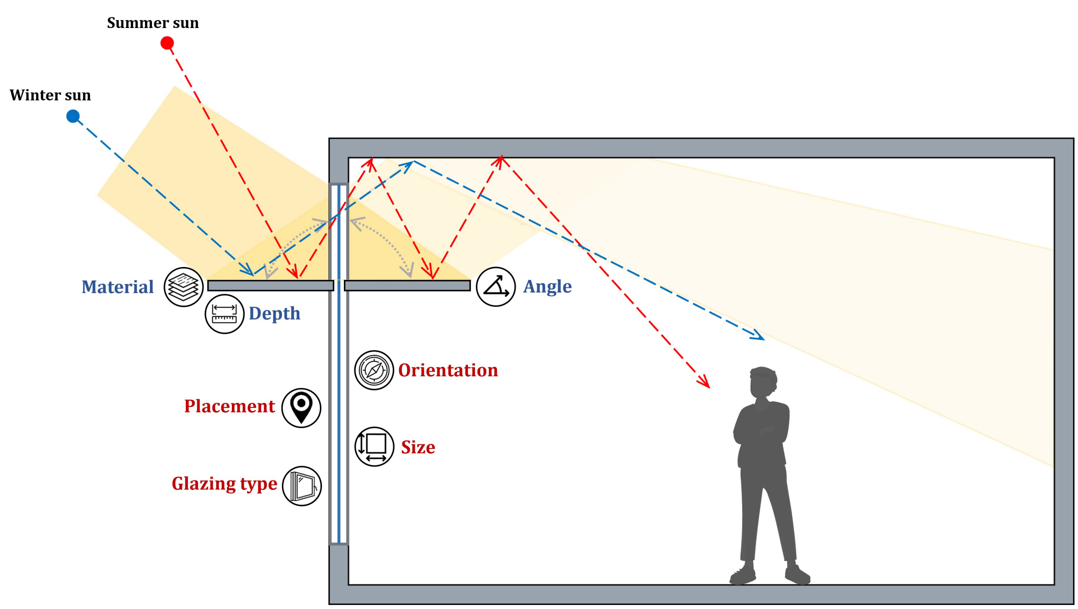

Fig. 1. Important design factors that influence redirecting natural light (parameters of the window in blue and light shelf design parameters in red).

influences the thermal and visual comfort of occupants in office buildings Distinguished from prior studies, this research introduces a fresh approach to designing windows and light shelves within office structures [16,17,26,27] and a comprehensive framework has been developed, combining advanced computational algorithms and building performance simulations. This framework allows architects and engineers to consider multiple objectives simultaneously, including thermal and visual comfort. By exploring various design alternatives early on, informed decisions can be made.

The significance of this investigation lies in its contribution of new knowledge and insights into the intricate interplay among window design, light shelves, and the overall performance of office buildings. Moreover, a unique combination of variables was introduced to examine the impact of window light shelf design, including the incorporation of a shading control strategy scenario in a first-in-light shelf design. The results highlight the potential for attaining design solutions that harmonize energy efficiency with occupant well-being. This research contributes to the advancement of sustainable building design practices and provides a valuable resource for professionals seeking to enhance the performance of office buildings through innovative design strategies.

2. Literature review

Much previous research has been on using light selves and the impact of proper window design on the occupants' comfort and buildings' energy consumption. As a popular shading device, a light shelf reduces solar gains while redistributing sufficient natural illuminance into the interior space [37]. This system is easily adjustable and offers various passive design strategies. It can be installed as a window addition for both interior and exterior spaces. Light shelves come in various shapes, ranging from flat to curved reflective surfaces, and can be controlled actively [41]. Unlike most shading systems that need relatively large spaces to be installed, light shelves require relatively small spaces [39], and they can be applied to overcome visual discomfort hazards and control indoor illuminance. This device can increase or decrease the incoming light flux in interior spaces depending on climate conditions [42].

According to the reviewed previous research, the annual number of papers studied on the window and light shelf system

Table 1. List of relevant documents in multi-objective optimization of windows and light shelves (E: educational, O: office, R: residential).

Source	Method	Light shelf	Window	Thermal comfort	Visual comfort	Design variable(s)	Objective function(s)	Case study space	Climate and region	Software platform
[24]	Simulation	×	✓	×	✓	WWR	Uniformity P1/P2, DGI	O	Netherlands, Amsterdam, Cfb	EnergyPlus
[17]	Simulation	✓	×	×	✓	Width, angle, and specularity of light shelves	ASE, sDA	E	Indonesia, Bandung, Af	DIVA
[15]	Simulation	✓	✓	×	✓	WWR, shading length, viewpoint, glass transmission, colorful glass	DGP	E	Iran, Yazd, BWh	Honeybee Plus, Ladybug
[23]	Simulation	×	✓	×	✓	Dimension and location of the window	ASE, sDA	O	Iran, Tehran, BSk	Honeybee, Ladybug
[28]	Simulation	×	✓	✓	✓	Building orientation, WWR, glazing material	Indoor thermal environment performance, Indoor visual performance	O	China, Xi'an, Cfa	EnergyPlus
[6]	Simulation	×	✓	✓	×	Building orientation, Window glazing material, overhang angle and depth	PMV, PPD, time-weighted discomfort, long-term percentage of dissatisfied	O	China, Hohhot (BSk), Tianjin (Dwa), Shanghai (Cfa), Guangzhou (Cfa)	EnergyPlus, jEplus + EA
[29]	Simulation	✓	×	✓	×	Angle, depth, and number of light shelves	PPD	R	Iran, Mashhad, BSk	Honeybee, Ladybug
[30]	Simulation	×	✓	✓	✓	Building orientation, WWR, number of windows, glazing material	UDI, DA, TEUI, LEUI, CRT	E	Iran, Tehran, BSk	Honeybee, Ladybug
[22]	Simulation	✓	×	×	✓	Height, angle, and depth of light shelves	UDI, DGP	O	Malaysia, Penang, Af	Honeybee, Ladybug
[31]	Simulation	✓	×	✓	✓	WWR, height, length, and angle of light shelves	UDI, ASE, sDA, comfort ratio	E	Iran, Sari (Csa), Tehran (BSk)	OpenStudio, Honeybee, Ladybug

has increased significantly in the last decade. The rise is attributed to advancements in simulation software, heightened focus on occupant comfort and energy efficiency in architectural design, and architects' endeavors to integrate passive design solutions like light shelves to harness renewable energy. In order to enhance the literature review and categorize existing research, certain studies have been organized within Table 1. The most significant points of these papers are also included in this table.

Light shelves play a significant role in directing and optimizing incoming sunlight, enhancing occupants' visual comfort in interior spaces. The effectiveness of light shelves depends on a range of factors, such as geometry, materials, scale, inclination angle, and the climate conditions of the building site [43]. Numerous studies have explored the influence of shading devices, adaptive façades, and their control strategies on comfort and energy use in buildings. Pereira de Castro [32] analyzed a case study in Rio de Janeiro and highlighted that how lightshelves can effectively reduce glare and solar heat gain near windows while enhancing natural lighting in rooms. Cruz Silva et al. [33] suggested that redirecting sunlight through well-designed systems like louvers and horizontal light shelves can effectively filter solar radiation, ensuring adequate illuminance levels and uniform light distribution in university buildings of Brazil.

Krüger and Zannin [34] indicated that light shelves can reduce indoor lighting levels by casting shadows on the façade and distributing light to the ceiling. Lim et al. [35] simulated an office in Malaysia, finding that modifications to glass types and the addition of interior light shelves could greatly improve visual comfort. Shen and Tzempelikos [36] demonstrated that indoor light shelves can mitigate glare and enhance comfort. Berardi et al. [37] showed that louvers could increase illuminance by up to 70% through on-site measurements and simulations. Berardi and Wang [38] further affirmed that proper shading design is key to controlling glare and improving visual comfort. Anaraki [26] focused on light shelf systems in Toronto offices, revealing that they significantly boost the useful daylight illuminance (UDI) close to windows. Lim and Heng [27] reported that without light shelves, visual comfort is markedly low, whereas a well-designed system can reduce illuminance rates by 34.1–62% and enhance light distribution uniformity by up to 178.6%. Acosta et al. [39] examined visual comfort and glare in residential spaces and evaluated the WWR, shape, size, position of the window, and its reflection on the wall. They concluded that windows in a higher position had more visual comfort at the end of the room than the center windows.

Delvaeyea et al. [40] found that a solar control system could save between 18 - 46% of energy. According to their results, shading system performance in visual comfort is directly related to the initial conditions. Amundadottir et al. [41] examined the the steady-state two-dimensional convenience-making process by investigating a new approach. They examined three daily performance indicators: visual interest, visibility behavior, and non-visual health potential. The study findings indicated that the illuminance distribution directly affects all three metrics, although the impact of the daily time could be trivial. Lee et al. [20] discovered that perforated light shelves could potentially increase lighting energy usage compared to non-perforated ones. Lee [42] also looked at the angle of light shelves and found improvements in indoor uniformity and visual comfort, even integrating solar cells for energy supply.

Kim et al. [18] combined light shelves with dimming controls, achieving a 3.4–59.6% reduction in energy consumption. Attia et al. [43] developed a survey to evaluate automated shading in offices, indicating that higher WWRs are more susceptible to glare. Cheong et al. [44] proposed using light shelves to enhance visual comfort and reduce energy needs by 5.55% in a Singaporean building. Ebrahimi-Moghadam et al. [29] analyzed the design variables of the interior light shelves through a parametric study. They concluded that using optimal light shelves leads to an 81% improvement in occupants' thermal comfort and a 20% reduction in the energy consumption of the residential building. Furthermore, Tabadkani et al. [5] analyzed the impact of an automatic shading control scenario and its activation threshold on the occupants' comfort condition and energy demand of buildings in different climatic conditions. According to their findings, climatic conditions significantly affect the shading control strategy, and applying solar radiation is the most productive control trigger to identify the optimum control strategy for each city.

Valitabar et al. [45] improved daylighting and outdoor views by up to 47% in a Tehran office with an advanced control strategy. Lastly, Norouziasas et al. [46] performed a comprehensive simulation-based analysis with unique control scenarios recommended by ISO/DIS 52016–3. The outcomes associated with the base model (i.e., fixed shading) and no shading strategy were analyzed to evaluate the impact of control strategies adopted from ISO 52016-3. Their results indicated that applying the recommended control scenario leads to a significant reduction in the cooling load of the building in comparison with the base case and no shading strategy. Most previous research on window and sun-shading design has not adequately addressed the significant role of occupant behavior in designing window and light-shading systems. Consequently, there is a lack of occupant-centric architectural design models for the window and light shelf.

In general, new policies should be developed to establish an up-to-date window and light shelf design standard in developing countries. Current standards only focus on limited design variables of window and shading devices. Some of them aren't even optimized for all climates [16]. Given the positive impact of shading control strategies on occupants' comfort, further in-depth studies on control strategy as a pivotal design variable in optimizing windows and light shelves are recommended, particularly in regions where buildings primarily rely on active design strategies [15]. Architects and building designers should use more passive attachments like light shelves in building designs as far as possible. Utilizing passive strategies aids in reducing building energy consumption, thereby decreasing reliance on fossil fuels to provide occupants' comfort and contributing to enhanced air quality through reduced CO_2 emissions [47]. Therefore, this research aims to bridge the gap by exploring how occupant behavior interacts with windows, light shelf systems, and energy consumption in architectural design.

3. Methodology

This research aims to propose a multi-objective optimization design for window and light shelves in office buildings. To this end, an office building in the semi-arid climate of Tehran was selected and developed using Grasshopper parametric software. Afterward, the Honeybee energy and daylight plugin was employed for simulating thermal and visual conditions, and finally,

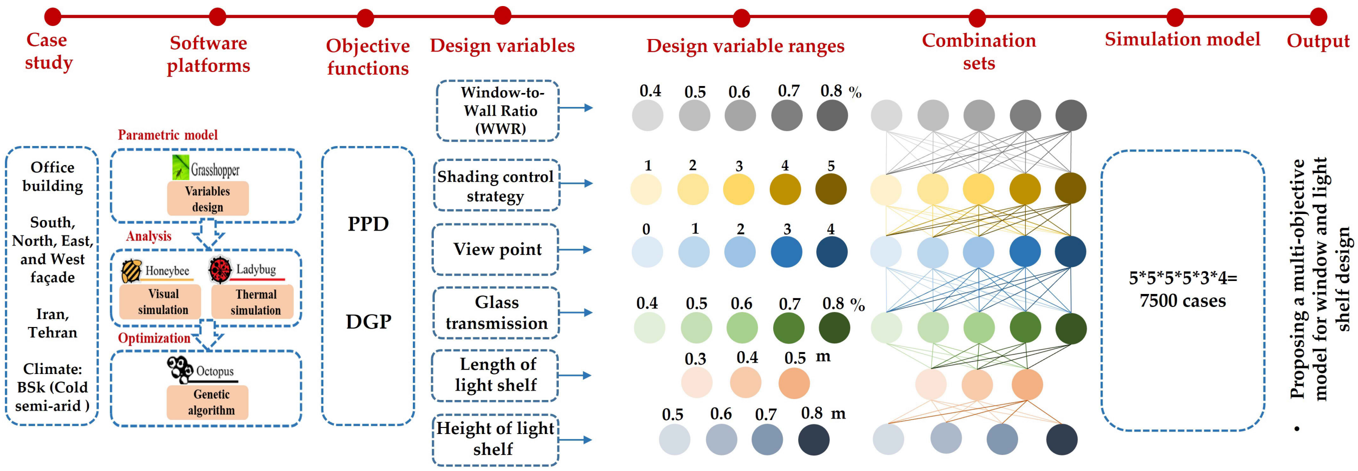

Fig. 2. Flowchart of research method.

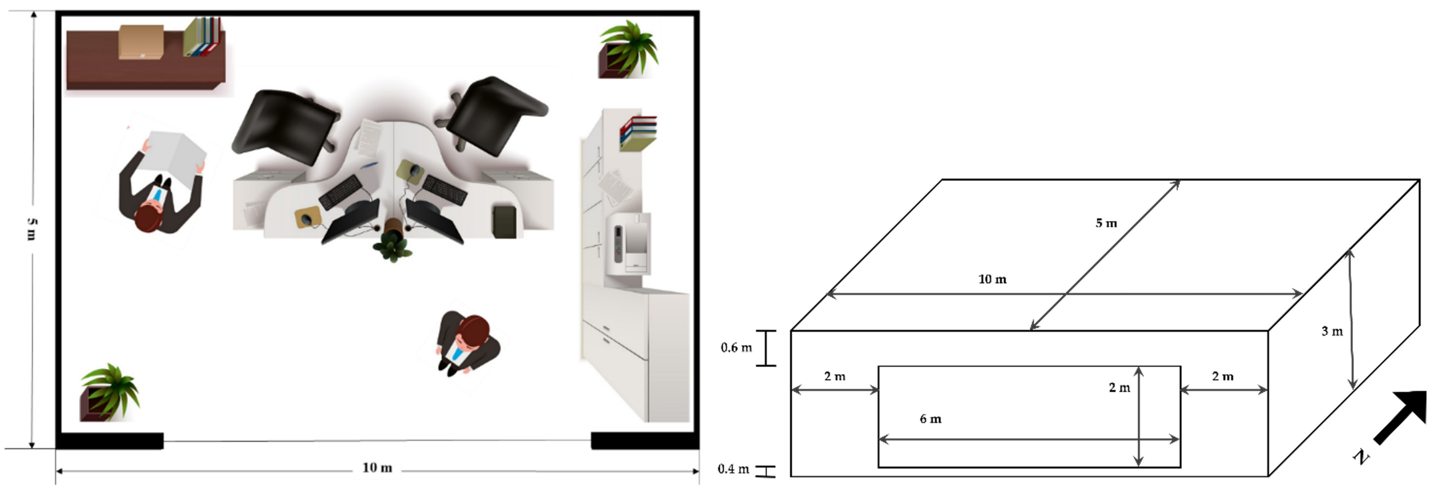

Fig. 3. The geometry of the office room.

multi-objective optimization was conducted with the Octopus plugin. The various stages of the research procedure are illustrated in Fig. 2 to enhance comprehension of the research flowchart:

3.1. Case study description

This study focuses on optimizing the design features of windows and light shelves for an office building unit located in Tehran (Iran). The building is oriented towards the south to maximize natural light absorption from the sun's path in the region [48]. It is assumed that the office unit is situated on the middle floor of the building. Consequently, heat transfer occurs solely through the external wall that contains a window, while all other room enclosures are internal and do not facilitate heat transfer. The office space in the Rhino has dimensions of 10 m x 5 m x 3 m (length x width x height) as shown in Fig. 3. Typically, these measurements are utilized for standard-sized office spaces in Iran [47].

The building material specifications for this unit are derived from the Iranian National Building Regulations [49], while the thermal characteristics of the construction are based on ASHRAE 90.1-2010 [50]. Hoseinzadeh et al. compared a comparison between materials specified by ASHRAE and Iran's national standard. Their findings indicate that the material recommended by ASHRAE outperforms the latter [51]. The double-glazing window is installed on the external wall, providing a 40% WWR. A packaged terminal heat pump air conditioner (PTHP) is installed in the room, and its capacity is automatically estimated based on the coldest and the hottest days of the year. This study assumes that the reflectivity value and the specularity value of the light shelf are 0.8 and 0.9, respectively. It is also worth mentioning that the considered decision variables are the height and length of the light shelf.

During weekdays from 8:00 to 17:00, the heating and cooling setpoint temperatures were adjusted to 22 °C and 26 °C, respectively. It should be noted that the workweek in Iran runs from Saturday to Wednesday. Outside of office hours, the setback temperature for heating is 18 °C, while the setback temperature for cooling is 30 °C. The office room is assumed to accommodate 5 individuals with a metabolic rate of 125 W/person, and their clothing level (CLO value) is based on the ASHRAE 55 guidelines [52]. The average fresh rate intake rate is presumed to be 9.44 L/s per person [53]. The office follows a specific schedule for occupancy, lighting, and electric equipment based on the weekdays in Iran, from Saturday to Wednesday.

The schedule ensures that the office is occupied during typical working hours, with occupancy gradually increasing from hour 7 to reach 90% from hours 9 to 11. The occupancy remains at 90%

Table 2. Radiance and optimization parameters.

Radiance parameter	**Value**
Ambient bounces (ab)	2
Pixel threshold (pt)	0.15
Pixel sample jitter (pj)	0.6
Direct threshold (dt)	0.5
Direct sampling (ds)	0.5
Direct jitter (dj)	0
Pre-sampling density (dp)	64
Limit weight (lw)	0.05
xScale	1
yScale	1
Ambient divisions (ad)	1024
Direct certainty (dc)	0.25
Ambient supersamples (as)	1024
Ambient value (av)	0
Limit recursion (lr)	4
Pixel sample (ps)	8
Ambient resolution (ar)	128
Ambient accuracy (aa)	0.25
Specular threshold (st)	0.85
Specular jitter (sj)	0.3
Optimization parameter	**Value**
Elitism	0.5
Mutation rate	0.1
Cross over rate	0.6
Population size	50
Number of generations	20

until hour 16, after which it decreases to 50% at hour 17. From hour 18 onwards, the office is unoccupied, and both the lighting and electric equipment are turned off. This schedule promotes energy efficiency by aligning the use of lighting and electric equipment with the presence of occupants in the office. It also is assumed that the electrical equipment of the office is only available during office hours and consumes 450 W constantly. During working hours, a fluorescent lighting system with a power capacity of 500 watts is employed. The automatic dimmer controls the power, with the sensor positioned at desk height in the middle of the room (0.8 meters above the floor) [53].

3.2. Location and climate

To conduct the simulation, the ITMY file for Tehran-Mehrabad (407540) is imported into the Ladybug plugin, which can be downloaded from the EnergyPlus website. Tehran, the capital of Iran, situated at 35.7219° N and 51.3347° E latitude and longitude, with an elevation of 1219 meters. Over an 18-year period, meteorological station data from the Tehran International Exhibition shows July 10 to August 10 as the warmest period and February as the coldest. Tehran experiences approximately 44.7% mean cloud cover. Based on the Köppen-Geiger climate classification, Tehran falls under the category of a cold semi-arid climate (BSk) [54]. This climate is characterized by relatively low precipitation and a large temperature range between seasons. The city experiences cold winters and hot summers. The heating degree days (HDD) in Tehran amount to 1810, indicating the demand for heating during the colder months, while the cooling degree days (CDD) reach 865, reflecting the need for cooling during the warmer months [55]. These climatic conditions play a crucial role in determining the thermal and visual comfort requirements for building design in Tehran [30].

3.3. Building Performance Simulation

Rhinoceros is a computer-aided design (CAD) software created by Robert McNeel & Associates. Its environment is derived from the NURBS numerical model, which focuses on generating a scientifically accurate depiction [56]. Robert McNeel & Associates [57] have created Grasshopper as a visual plugin for Rhino, which provides parametric evaluation [25]. Mustafa Roudsari introduced the Ladybug in 2013 for energy analysis purposes. It is crucial to choose the correct simulation software to obtain optimal results for the objective functions. For this study, Grasshopper 1.0.0007 version in the Rhino 6 (SR16) has been applied for developing the parametric model, and visual and thermal analysis has been performed with the assistance of the Honeybee and Ladybug plugins version of 0.0.66 [25]. This study considered the simulation timestep at 14:00 on the winter solstice day (December 21). The Octopus plugin is also used to optimize and assess the answers. The basis of octopus is the Pareto Evolutionary Algorithm (SPEA-2) that is combined with the Hypervolume Estimation Algorithm (HypE) [58,59]. In addition, the Radiance and optimization parameters used in the research were tabulated in Table 2.

3.4. Thermal comfort

According to ISO Standard 7730:1994 [60], and ASHRAE Standard 55 [61], thermal comfort is expressed as "that condition of mind which expresses satisfaction with the thermal environment" [62,63]. The assessment of thermal comfort is influenced by various factors, such as temperature, thermal radiation, humidity, air velocity, activity level, and clothing insulation [30,64]. The Predicted Mean Vote (PMV) index that was introduced by Fanger [65,66] is applied in this research. The six mentioned parameters have been combined in which PMV is between -0.5 to +0.5. The values less than 10% present the ideal range for the Predicted Percentage of Dissatisfied (PPD) [61].

3.5. Visual comfort

Visual comfort is "the state of mind that expresses satisfaction with the visual environment" [67]. Too much or too little light also causes occupants visual discomfort and threatens their satisfaction and efficiency [68]. Visual comfort has been assessed by several factors related to human needs and the light environment, like light distribution, quality of light, glare, and amount of light [15]. Previous studies show glare has been the most reliable criterion for evaluating visual comfort [69,70]. Glare is" the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility" [71].

Given its complexity and subjectivity, various methods exist to forecast or assess discomfort glare risks. DGP, commonly used for evaluating daylight glare, was introduced in [72] and validated in subsequent works, with an optimal range of 0.35 for office settings [29]. Values below 0.35 indicate "Imperceptible glare," where glare is not bothersome. Ranging from 0.35 to 0.4, DGP signifies "Perceptible glare," suggesting noticeable but bearable glare. Within the 0.40 to 0.45 range, DGP signifies "Disturbing glare," indicating increased discomfort. DGP exceeding 0.45 is termed "Intolerable glare," signifying significant discomfort and reduced visual comfort and performance [30,69].

3.6. Design variables and objective functions

The main goal of this study is to choose the appropriate architectural specifications of windows and light shelves for office buildings. Therefore, the window-to-wall ratio (WWR), the shading control strategy, the viewpoint (VP), the transmission of glass (TG), light shelf length (LSL), and light shelf height (LSH) are selected as design variables. Changing the TG value of a window can have an indirect impact on the SHGC and a direct impact on the VT. However, the U-value is primarily influenced by other factors, such as the window frame material and glazing type. It's important to note that the specific relationship between TG, SHGC, VT, and other window parameters can vary depending on the window design, glazing technology, and coatings used. Additionally, it is worth mentioning that the window's height from the ceiling is always constant for different WWRs. The initial height considered for the light shelf from the ceiling is 60 cm (generally, in this research, this height is between 50 and 80 cm from the ceiling).

This research uses a multi-objective optimization method to optimize window and light shelf system characteristics to enhance occupants' thermal and visual comfort in an office space. Multi-objective optimization algorithms try to generate solutions that are close to the Pareto-optimal (non-dominated) solutions. When the optimal solutions are obtained, decision-makers select the final resolution according to the desired objectives and personal preferences [23]. The objective function of indoor thermal comfort is the PPD, and the annual average of DGP is considered the objective function of visual comfort. The calculation of objective functions is carried out during office hours. Considering that glare is very dependent on the observer's position and viewing angle, the analyses were done from four points of view. These points were at 0.8 meters from the south wall and were respectively separated by one-meter steps from the east wall (based on the seating arrangement in the office).

3.7. Shading control strategies

Shading control strategies must be designed to perform properly under climatic conditions. Control strategies will work very differently according to the different climatic conditions. Regarding energy-saving, it is recommended that manual control be avoided in office buildings since the previous studies indicated that users often adjust the shading systems regardless of cooling/heating needs or optimal comfort levels [57]. Recently, ISO 52016–3 proposed new control strategies for offices with adaptive façades [46]. Adaptive façade elements in buildings are classified into three categories: dynamic solar shading, chromogenic glazing, and active ventilated façade [73]. Light shelves as a shading device can be placed under the first category. In this research, the light shelf is controlled to optimize daylight penetration while minimizing glare and excessive solar heat gain.

The control strategy relies on sensors to measure available daylight and occupancy levels, allowing for automatic adjustment of the light shelf's position. The fixed nature of the light shelf ensures consistent daylight redirection throughout the day without the need for manual or automated retraction. It possesses visual properties that enhance daylighting, and reduce glare, and thermal properties that mitigate solar heat gain. The simulations considered these properties, evaluating the light shelf's impact on daylight levels, glare control, and thermal comfort. Overall, the light shelf's design and control contribute to improved visual comfort, reduced energy consumption, and a more pleasant indoor environment. Control strategies also include various specifications that can behave as different design variables. Accordingly, five shading control strategies are adopted in this research, each having distinctive effects on the occupant's comfort. These strategies are designed to regulate the shading systems in office buildings based on specific conditions:

1. Always active: implies that the shading system is continuously activated, regardless of any specific setpoint unit.
2. Always disabled: means that the shading system always remains deactivated.
3. The activation of the shading system occurs when the total solar irradiance surpasses the predefined setpoint value, utilizing the total solar irradiance as the unit for comparison.
4. When the horizontal solar irradiance surpasses the designated threshold, the shading system is activated using the horizontal solar irradiance as the reference unit.
5. The shading system is disabled at night and activated during the day when both cooling demand and total irradiance are higher than the setpoint value, combining various activation conditions.

These shading control strategies provide options for regulating the shading systems in office buildings based on different criteria, such as solar irradiance and cooling demand. By selecting an appropriate strategy, occupants' comfort can be enhanced while optimizing energy efficiency.

3.8. Multi-objective optimization

Multi-objective optimization problems include different objective functions, and their complexity differs from single-objective problems. A set of solutions is generated called the Pareto front to optimize the objective functions. The set of solutions of the Pareto front is not superior to each other [6,28]. The multi-objective optimization problem can be described as follows [74]:

$$\begin{cases} Minimize F(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), \ldots, f_k(\vec{x})]^T \\ Subjectto: \begin{cases} \vec{g}(\vec{x}) \le 0 \\ \vec{h}(\vec{x}) = 0 \end{cases} \\ \vec{x} \in R^n, \vec{f}(\vec{x}) \in R^k, \vec{g}(\vec{x}) \in R^m \text{ and } \vec{h}(\vec{x}) \in R^q \\ X = \{\vec{x} | g_m(\vec{x}) \le 0, m = 1,2,3,\ldots,m\} \\ \{h_q(\vec{x}) = 0, q = 1,2,3,\ldots,q\} \\ S = \{F(\vec{x}) | \vec{x} \in X\} \end{cases} \tag{1}$$

In this context, the term $'\vec{x} \in R^{n}'$ represents the design variables, while $'n'$ denotes the number of decision variables. The number of objective functions is denoted by $'k'$ and is typically equal to or greater than 2. Furthermore, $'\vec{f}(\vec{x}) \in R^{k}'$ refers to the vector of

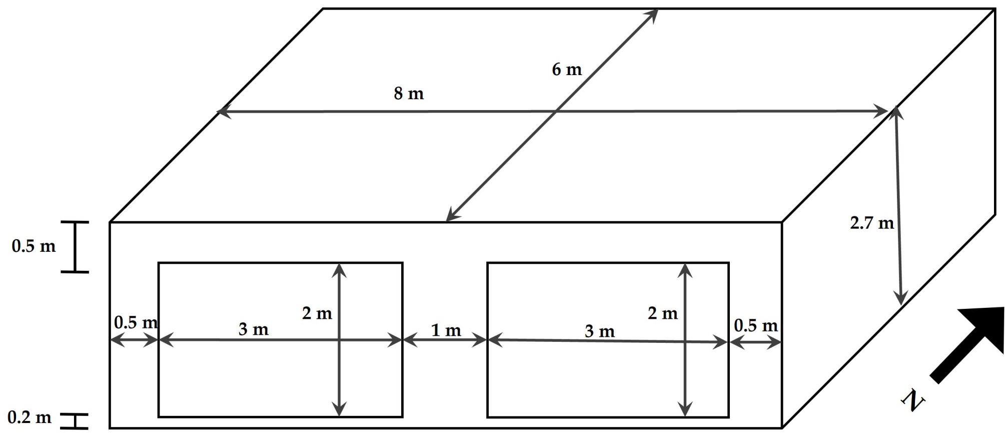

Fig. 4. Sample test case number 600 according to ASHRAE Standard 140-2017 [81].

Table 3. Radiance and optimization parameters.

Simulation Model	ESP	BLAST	DOE21D	SRES-SUN	SRES	S3PAS	TSYS	TASE	Statistics for example results				LBT
Organization or Country	DMU	US-IT	NREL	NREL	BRE	Spain	BEL-BRE	Finland	Min	Max	Mean	(Max-Min)/Mean (%)	Tehran, Iran
600 Base Case, South Windows	6.137	6.433	7.079	7.278	7.964	6.492	6.492	6.778	6.137	7.964	6.832	26.7	7.256
	4.296	4.773	5.709	5.226	5.596	4.882	4.872	5.362	4.296	5.709	5.090	27.8	4.922
	3.437	3.940	4.045	4.258	-	4.037	3.931	4.354	3.437	4.354	4.000	22.9	4.925
	6.194	5.965	6.658	6.827	-	6.286	6.486	6.812	5.985	6.827	6.461	13.3	6.725

these objective functions, where $\vec{f_i}(\vec{x})$: $R^n \rightarrow R^1$. Additionally, the number of inequality constraints and their vector are defined as $'m'$ and $'\vec{g}(\vec{x})'$, respectively. Similarly, $'q'$ and $'\vec{h}(\vec{x})'$ represent the number of equality constraints and their vector. Finally, $'X'$ represents the feasible decision, and $'S'$ denotes the criterion spaces [47,74].

3.9. Software validation

Recently, Honeybee and Ladybug plug-ins have been effectively validated in various studies [30,75-77]. So, this research utilized these plug-ins for visual and thermal simulations, with validation of the simulation model conducted in [5]. The validation process included fieldwork experimental illuminance data and relative ratios metric, following recommendations from earlier research. Horizontal illuminance served as the validation method. Therefore, this study presents key highlights, with the maximum average relative difference being around 5.9%. Farzam Kharvari [79] conducted a detailed comparison between simulation outcomes and field measurements under overcast conditions using Honeybee Plus version 0.0.04, powered by Radiance version 5.1. This study verified accuracy by cross-referencing results with three distinct illuminance levels under consistent sky conditions. Additionally, the research delved into how simulation parameters and model configurations influence result precision. Findings indicate that adhering to recommended Radiance settings yields satisfactory accuracy, with biases falling below 15%.

Consequently, this paper establishes a validated model for future investigations concerning shaders, light shelves, and other design elements reliant on daylight. In this part of the research, the building performance simulation results were evaluated by the ASHRAE 140 standard. ANSI/ASHRAE Standard 140-2020, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs [80], provides a set of tests for energy simulation programs for buildings. This method ensured that the Honeybee plugin simulation's results were accurate. Previous research has used this method to validate simulation tools and results [51,57]. The results from Honeybee version 0.0.66 in the current research were compared with the "BESTEST" diagnostic tests. The "BESTEST" tests aim to identify errors caused by plugins and software. In this paper, validation has been done by comparing the results of annual and peak heating and cooling loads. Validation is performed by case sample 600 (BESTEST) in ASHRAE 140–2017 standard [80]. Case number 600 pertains to Class I Test Procedures, which involve the analysis of software's capability to simulate building structures in a low-mass configuration (Fig. 4).

Case sample No. 600, selected for research conducted in this article, has a low mass. Also, the characteristics of materials in walls, floors, and light ceilings are presented in the standard. Honeybee could perform the validation of sample 600 (BESTEST), and the simulation results match the ASHRAE 140- 2020 standard validation. It is indicated that the obtained results have acceptable accuracy. The comparison of validation results with the BESTEST is tabulated in Table 3.

4. Results

In this section, the focus shifts to exploring the responses to the research inquiries and presenting the outcomes generated from the simulation. The simulation methodology has been used in the current paper to generalize the findings. According to the simulation results, the south orientation has the highest PPD value of 20.5%, indicating a greater amount of daylight entering through windows facing the south and the north orientation follows with a PPD value of 18.0%, suggesting a relatively high level of daylight penetration. Moreover, the west orientation has a PPD value of 13.9%, indicating a moderate level of daylight penetration and the east orientation has the lowest PPD value of 11.1%, suggesting the least amount of daylight entering through east-facing windows.

On the other hand, the east orientation has the highest DGP value of 0.51, suggesting a higher probability of experiencing glare when facing east and the South orientation follows closely with a DGP value of 0.49, indicating a relatively high probability of glare. In addition, the west orientation has a DGP value of 0.47, suggesting a moderate probability of glare and the north orientation has the lowest DGP value of 0.46, indicating a lower probability of experiencing glare. Based on this information, it can be observed that the south orientation provides the highest PPD, while the east orientation has the highest DGP. The north orientation has the lowest DGP value, indicating a lower probability of glare. Therefore, different strategies should be applied to select the proper decision variables from the obtained optimal solutions according to each window orientation.

In the next step, the Colibri tool was used in the Grasshopper environment to determine a multi-objective, light shelf design window and light shelf design model to improve occupants' thermal and visual comfort. According to the above explanation, 7500 cases were obtained, and the results were then uploaded to the Design Explorer site (site address: https://tt-acm.github.io/DesignExplorer/), an online open-source tool, and Fig. 5 is generated. As illustrated in Fig. 5, the optimization procedure yields various optimal solutions. Then, the minimum values by which the occupants' comfort is provided (i.e., the DGP values below 0.35 and the PPD values below 10%) are chosen as proper solutions for every orientation.

As it is clear from Fig. 5, the results are mainly in the range of DGP below 0.28 and above 0.55 and PPD above 10%. Considering that DGP is imperceptible in the range of 0.2 to 0.35 and PPD below 10% is also acceptable, the results in these ranges are magnified, as shown in Fig. 6, to determine which design variables satisfy occupants' comfort. As shown in Fig. 6, only 145

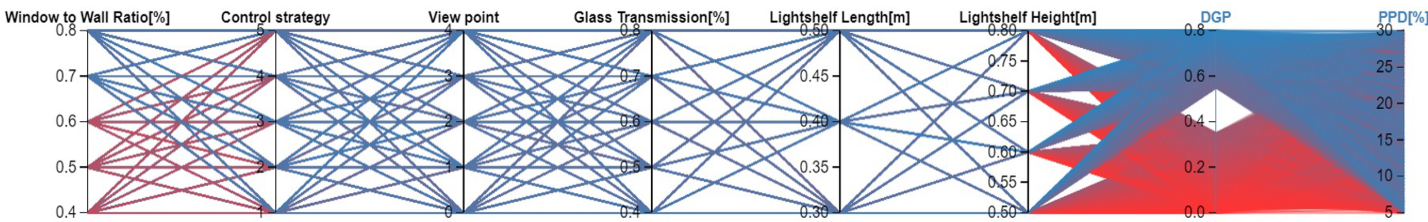

Fig. 5. Combination of the physical parameters of the window and light shelves in the south-facing window.

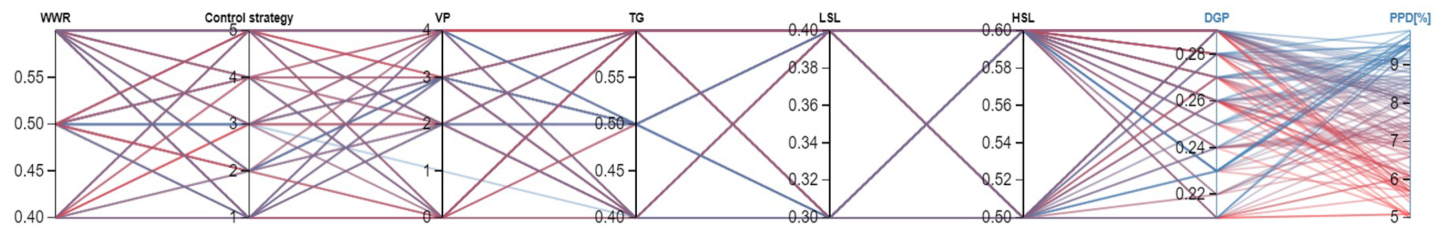

Fig. 6. Magnification of DGP results between 0.2 to 0.35 and PPD between 5% to 10%.

Table 4. Some of the optimized combinations of the physical parameters of the window and light shelves for the south-facing window in Tehran (R: range, I: interval, and IV: initial value).

WWR (%)			Shading control strategy No. (See 3.7)			VP			TG (%)			LSL (m)			LSH (m)			DGP	PPD (%)
R	I	IV	R	I	IV	R	I	IV	R	I	IV	R	I	IV	R	I	IV		
0.4-0.8	0.1	0.4	1-5	-	No. 2	0-4	1	1	0.4-0.8	0.1	0.8	0.3-0.5	0.1	0.4	0.5-0.8	0.1	0.6		
0.4			5			4			0.5			0.4			0.5			0.29	5.4
0.4			3			3			0.4			0.3			0.5			0.21	5.1
0.4			3			3			0.4			0.3			0.5			0.28	5.1
0.5			2			4			0.6			0.4			0.5			0.21	5.1
0.5			5			2			0.4			0.3			0.6			0.24	5.1
0.5			2			2			0.4			0.4			0.6			0.27	5
0.6			3			0			0.5			0.4			0.6			0.25	5.1
0.6			3			2			0.4			0.4			0.6			0.26	5.6
0.6			2			4			0.6			0.3			0.6			0.26	5

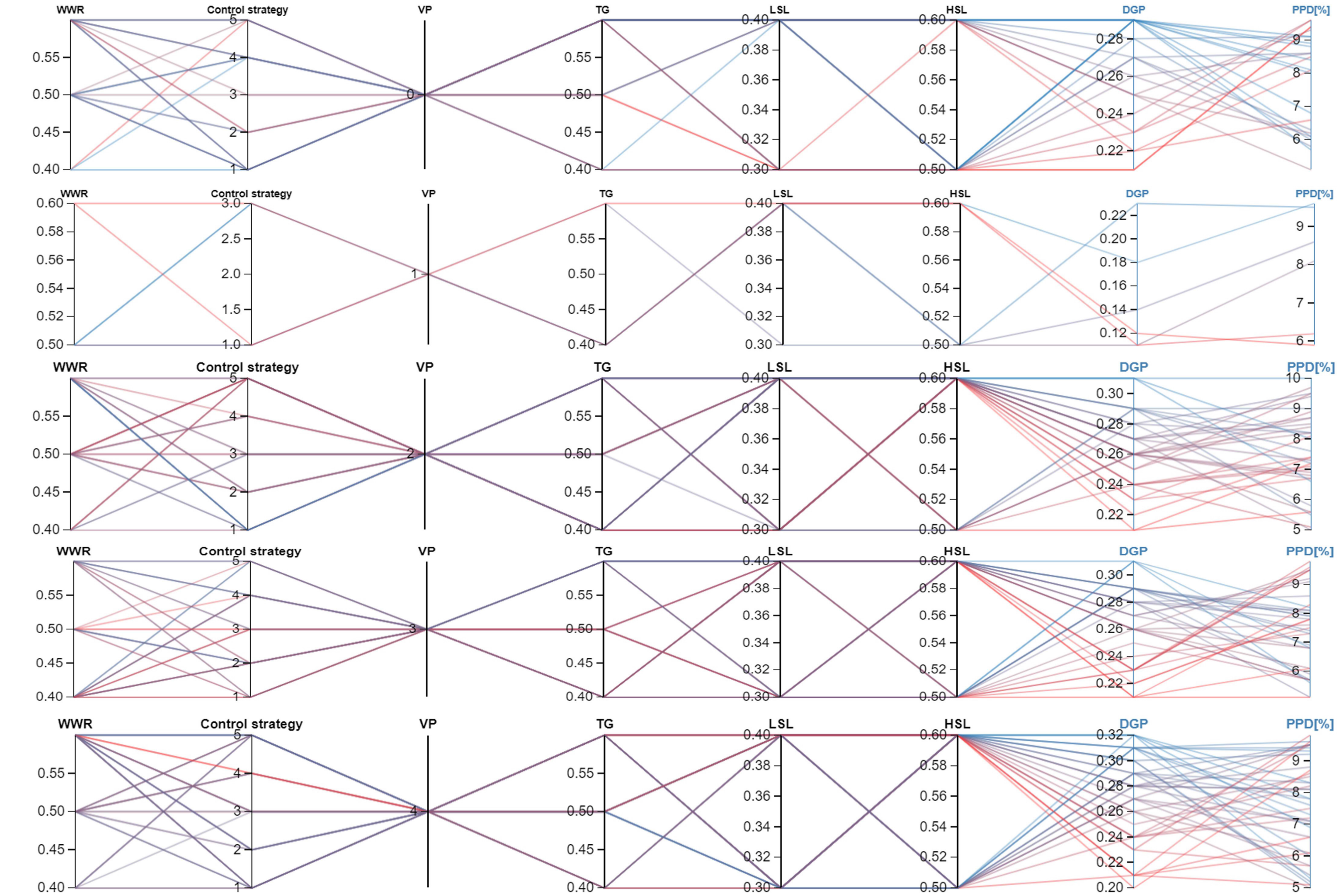

Fig. 7. Combination of the physical parameters of the window and light shelves in different viewpoints.

cases are in PPD results below 10% and DGP results between 0.2 to 0.35.

As can be observed from the figure, WWR in the range of 70% and 80% does not affect improving the occupants' comfort. Still, WWR results between 40% to 60% by choosing the appropriate control strategy in all VPs, reduces PPD below 10%, and simultaneity DGP values remain in the range of 0.2 to 0.35 (imperceptible glare). Similarly, it can be found that the acceptable range for TG, LSL, and HSL is 0.4-0.6, 0.3-0.4, and 0.5-0.6, respectively. Some of the optimized combinations of the physical parameters of the window and light shelves are shown in Table 4.

According to the study findings, an appropriate shading control strategy with an adequate activation threshold can improve the quality of occupants' comfort. The results show that the optimal shading control strategy differs according to the window orientation. It is worth mentioning that although the HVAC system is disabled outside of office hours, the shading control is always active. For example, in the west window, the light shelf system is activated when the office temperature exceeds 16.8 °C. It can directly affect the PPD and DGP values, respond without any delays, and improve occupants' comfort. As mentioned previously, thermal, and visual comfort are directly related to the position and view angle of the observer. Accordingly, in this research, different viewpoints of the observer were examined to determine that the occupants' comfort was satisfied in all the desired points. As can be observed from Fig. 7, it is possible to eliminate glare and provide occupants' thermal comfort with the appropriate selection of design variables considered in this paper.

4.1. The overall best answers

Architects can choose any solution from the obtained solutions. However, some extreme solutions might perform the best in some aspects irrespective of the other performance. To achieve the overall best solutions from the obtained answers, Equation (2) was applied. This Equation is derived from Zhang and Huang's research [44]. It provides the overall best optimal solution as a trade-off of the two objective functions in which it chooses the closest origin point within the Pareto front:

$$Overall_{best} = Min\left(\sqrt{\left(\frac{PPD_i - PPD_{min}}{PPD_{min}}\right)^2 + \left(\frac{DGP_i - DGP_{min}}{DGP_{min}}\right)^2}\right) \quad (2)$$

where PPD and DGP are the objective functions of thermal and visual comfort, respectively, on the other hand, "I" refers to the result of iteration, and "min" indicates the minimum value in the set. The overall best solutions for each orientation are presented in Table 5.

4.2. Unveiling the synergy of the integrated window and light shelf design on occupants' comfort

Comparing the optimum and initial objective functions in four orientations indicates that the greatest reduction in PPD and DGP

Table 5. Optimum decision variables for each orientation.

Decision variables	Unit	Orientation			
		South	West	North	East
WWR	%	0.6	0.4	0.5	0.6
Shading control strategy No.	-	2	5	5	3
VP	-	3	4	0	1
TG	%	0.4	0.6	0.5	0.5
LSL	m	0.4	0.3	0.3	0.3
LSH	m	0.6	0.5	0.6	0.5

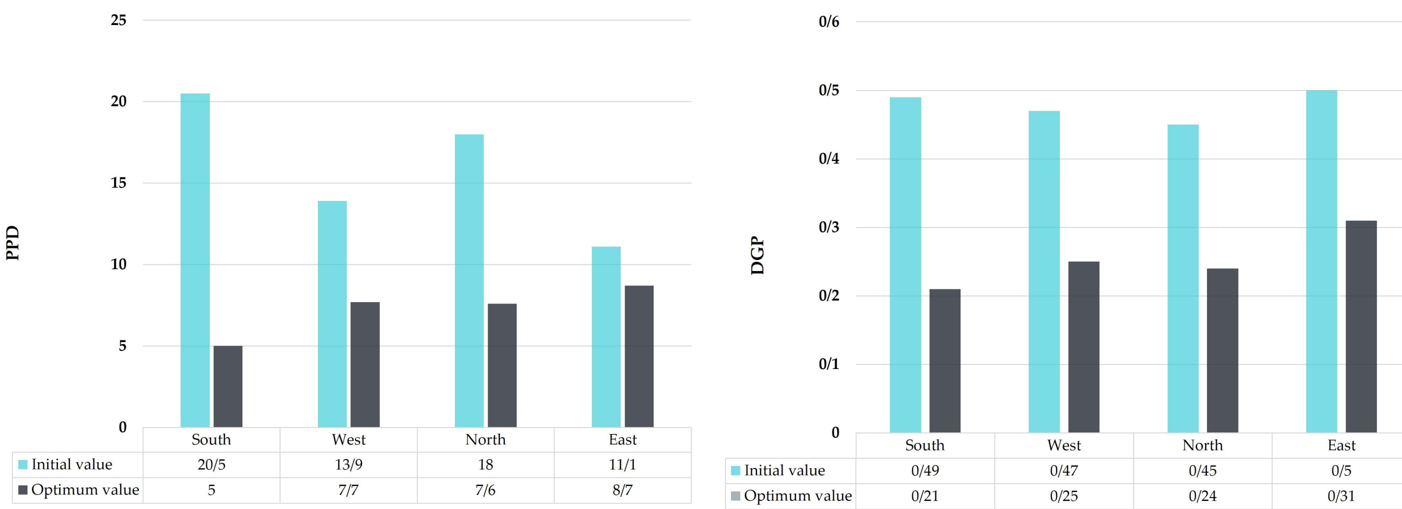

Fig. 8. Comparison of initial and optimum PPD and DGP.

values has been achieved in the south-facing windows. The least impact is observed in the west-facing ones (Fig. 8). The proposed multi-objective model is most efficient in office buildings with south-facing windows. It can be used as a suitable guideline for windows and light shelves design by architects and designers in the early design stage. Moreover, according to the study findings, PPD and DGP decreased by about 18.5–70.1% and 9.3–57.1%, respectively, compared to the base model.

Moreover, applying the proper shading control system and selecting the optimal variables for window and light shelf design positively reduces the cooling and heating demands and energy costs in office buildings, which can be evaluated in future research.

5. Discussion

In this section, the most important and tangible research findings are described below, and then the recommendations, strengths and limitations, and future perspectives of the study are discussed.

- According to the study, none of the design variables used in this research are conclusive and should be selected collectively based on the conditions. So, there is a significant relationship between PPD and the length/height of the light shelf regarding WWR. In optimum cases, the length of the light shelf is increased, and the height of it is dropped when WWR decreases. Overall, the results confirm that WWR and selecting an appropriate control strategy have the greatest impact on achieving occupants' comfort [47].
- In all directions, the objective functions (PPD and DGP) are not provided in cases with a WWR of more than 70%. On the other hand, by selecting an appropriate control strategy in the cases with WWR of 40% to 60%, the occupants' comfort can be satisfied in all directions.
- The findings present that the optimal design of window and light shelves in south orientation cases greatly impacts occupants' comfort. Still, this approach in the west-facing cases has an insignificant impact on improving occupants' comfort. In the west direction, alternative approaches should be considered or design variables adjusted to achieve the desired level of occupants' comfort.
- The study indicates highly remarkable differences between the initial and optimum values of PPD and DGP in south-facing cases. However, for a more accurate evaluation, it is necessary to consider the building energy usage as an objective function.

In general, new policies should be developed to establish an up-to-date window and light shelf design standard in developing countries. Current standards only focus on limited design variables of window and shading devices. Some of them aren't even optimized for all climates [16]. Given the positive impact of shading control strategies on occupants' comfort, further in-depth studies on control strategy as a pivotal design variable in optimizing windows and light shelves are recommended, particularly in regions where buildings primarily rely on active design strategies [15]. Architects and building designers should use more passive attachments like light shelves in building designs as far as possible. Utilizing passive strategies aids in reducing building energy consumption, thereby decreasing reliance on fossil fuels to provide occupants' comfort and contributing to enhanced air quality through reduced CO2 emissions [47].

6. Conclusions

This study selected a private office building in Tehran as a case study to propose a multi-objective model for window and light shelf design. Diva-Grasshopper's plugins were applied for thermal and visual simulations where the multi-objective optimization procedure is examined with the Octopus plugin. The objective functions of the study were the Predicted Percentage of Dissatisfied (PPD), the Discomfort Glare Probability (DGP), the window-to-wall ratio (WWR), shading control strategy, viewpoint, the transmission of glass, light shelf length, and light shelf height were considered as decision variables. Then, the effects of the combination of different physical parameters were considered using the simulation tool. A total of 7500 cases were obtained, of which only 145 were within the acceptable range of PPD and DGP. According to the results, occupants' comfort is not satisfying in cases with WWR of 70% and 80%. Accordingly, occupants' indoor thermal and visual comfort is satisfying in cases with WWR of 40% to 60% by choosing the appropriate control strategy in all VPs. Similarly, it can be found that the optimal range for TG, LSL, and HSL is 0.4-0.6, 0.3-0.4, and 0.5-0.6, respectively. For the Pareto front, the overall best Equation adapted from previous research was applied, and, in each orientation, the best configuration was selected regarding the occupants' thermal and visual comfort. Compared with the base cases in different orientations, the proposed model has improved the occupants' comfort in offices with south-facing windows. Still, it has less effect in improving the occupants' comfort in the west-facing ones. In addition, based on the results, PPD and DGP in all orientations dropped by 18.5–70.1% and 9.3–57.1%, respectively. Overall, this paper contributes to time and cost savings, ensures occupants' comfort, boosts employees' productivity, and promotes environmental conservation. It outlines future benefits of implementing optimized window and light shelf systems to enhance occupants' efficiency, aiding policymakers in setting standards and guiding architects in passive design strategies for future office constructions. Acknowledging its limitations, the study suggests potential enhancements like assessing objective functions more frequently and considering additional aspects of human comfort beyond thermal and visual elements. While the focus was on Tehran's office buildings, the study recommends exploring different climates to refine design variables. Future investigations could compare the efficacy of exterior and interior light shelves in enhancing occupants' comfort.

Contributions

All the authors contributed equally.

Declaration of competing interest

The authors declare no conflict of interest.

References

[1] Y. Sun, R. Wilson, and Y. Wu, A Review of Transparent Insulation Material (TIM) for building energy saving and daylight comfort, Applied Energy 226 (2018) 713-729.

[2] L. D. Labzovskii et al., What can we learn about effectiveness of carbon reduction policies from interannual variability of fossil fuel CO2 emissions in East Asia? Environmental Science & Policy 96 (2019) 132-140.

[3] A. Balali, A. Hakimelahi, and A. Valipour, Identification and prioritization of passive energy consumption optimization measures in the building industry: An Iranian case study, Journal of Building Engineering 30 (2020) 101239.

[4] E. Sorooshnia, M. Rashidi, P. Rahnamayiezekavat, and B. Samali, Optimizing Window Configuration Counterbalancing Energy Saving and Indoor Visual Comfort for Sydney Dwellings, Buildings 12 (2022) 1823.

[5] A. Tabadkani, A. Roetzel, H. Xian Li, A. Tsangrassoulis, and S. Attia, Analysis of the impact of automatic shading control scenarios on occupant's comfort and energy load, Applied Energy, 294 (2021) 116904.

[6] J. Zhao and Y. Du, Multi-objective optimization design for windows and shading configuration considering energy consumption and thermal comfort: A case study for office building in different climatic regions of China, Solar Energy, 206 (2020) 997-1017.

[7] T. Méndez Echenagucia, A. Capozzoli, Y. Cascone, and M. Sassone, the early design stage of a building envelope: multi-objective search through heating, cooling and lighting energy performance analysis, Applied Energy, 154 (2015) 577-591.

[8] W. Wang, H. Rivard, and R. Zmeureanu, Floor shape optimization for green building design, Advanced Engineering Informatics, 20 (2006) 363-378.

[9] J. C. Miles, G. M. Sisk, and C. J. Moore, the conceptual design of commercial buildings using a genetic algorithm, Computers & Structures 79 (2001) 1583-1592.

[10] J. E. Woods, Cost avoidance and productivity in owning and operating buildings, Occupational Medicine 4 (1989) 753.

[11] A. Zhang, R. Bokel, A. van den Dobbelsteen, Y. Sun, Q. Huang, and Q. Zhang, Optimization of thermal and daylight performance of school buildings based on a multi-objective genetic algorithm in the cold climate of China, Energy and Buildings 139 (2017) 371-384.

[12] K. S. Lee, K. J. Han, and J. W. Lee, the impact of shading type and azimuth orientation on the daylighting in a classroom-focusing on effectiveness of façade shading, comparing the results of DA and UDI, Energies 10 (2017) 635.

[13] S. Grynning, B. Time, and B. Matusiak, Solar shading control strategies in cold climates - Heating, cooling demand and daylight availability in office spaces, Solar Energy 107 (2014) 182-194.

[14] F. Ascione, N. Bianco, R. F. De Masi, G. M. Mauro, and G. P. Vanoli, Design of the building envelope: A novel multi-objective approach for the optimization of energy performance and thermal comfort, Sustainability 7 (2015) 10809-10836.

[15] M. Pourahmadi, M.A. Khanmohamadi, and F. Mozafar, Windows optimization based on the glare performance in educational building of Iran hot and dry climate, Journal of Sustainable Architecture and Urban Design 7 (2019) 113-128, 2019.

[16] A. Faraji, F. Rezaei, P. Rahnamayiezekavat, M. Rashidi, and H. Soleimani, Subjective and Simulation-Based Analysis of Discomfort Glare Metrics in Office Buildings with Light Shelf Systems, Sustainability 15 (2023) 11885.

[17] R. A. Mangkuto, F. Feradi, R. E. Putra, R. T. Atmodipoero, and F. Favero, Optimisation of daylight admission based on modifications of light shelf design parameters, Journal of Building Engineering 18 (2018) 195-209.

[18] K. Kim, H. Lee, H. Jang, C. Park, and C. Choi, Energy-saving performance of light shelves under the application of user-awareness technology and light-dimming control, Sustainable Cities and Society 44 (2019) 582-596.

[19] G. Kim, H. S. Lim, T. S. Lim, L. Schaefer, and J. T. Kim, Comparative advantage of an exterior shading device in thermal performance for residential buildings, Energy and Buildings 46 (2012) 105-111.

[20] H. Lee, K. Kim, J. Seo, and Y. Kim, Effectiveness of a perforated light shelf for energy saving, Energy and Buildings 144 (2017) 144-151.

[21] M. Valitabar, A. Ghaffarian Hoseini, and S. Attia, Advanced control strategy to maximize view and control discomforting glare: a complex adaptive façade, Architectural Engineering and Design Management 18 (2022) 829-849, 2022.

[22] A. A. S. Bahdad, S. F. S. Fadzil, H. O. Onubi, and S. A. Ben Lasod, Sensitivity analysis linked to multi-objective optimization for adjustments of light-shelves design parameters in response to visual comfort and thermal energy performance, Journal of Building Engineering 44 (2021) 102996.

[23] P. Pilechiha, M. Mahdavinejad, F. Pour Rahimian, P. Carnemolla, and S. Seyedzadeh, Multi-objective optimisation framework for designing office windows: quality of view, daylight and energy efficiency, Applied Energy 261 (2020) 114356.

[24] C. E. Ochoa, M. B. C. C. Aries, E. J. Van Loenen, J. L. M. M. Hensen, E. J. van Loenen, and J. L. M. M. Hensen, Considerations on design

optimization criteria for windows providing low energy consumption and high visual comfort, Applied Energy 95 (2012) 238-245.

[25] S. Rabie, H. Sangin, and M. Zandieh, The Orientation of Village, the Most Important Factor in Rural Sustainability in Cold Climate (Case study: Masuleh and Uramantakht) 6 (2021) 761-776.

[26] U. Berardi and H. K. Anaraki, Analysis of the impacts of light shelves on the useful daylight illuminance in office buildings in Toronto, Energy Procedia 78 (2015) 1793-1798.

[27] Y.-W. Lim and C. Y. S. Heng, Dynamic internal light shelf for tropical daylighting in high-rise office buildings, Building and Environment, 106 (2016) 155-166.

[28] Y. Zhai, Y. Wang, Y. Huang, and X. Meng, A multi-objective optimization methodology for window design considering energy consumption, thermal environment and visual performance, Renewable energy, 134 (2019) 1190-1199.

[29] A. Ebrahimi-Moghadam, P. Ildarabadi, K. Aliakbari, and F. Fadaee, Sensitivity analysis and multi-objective optimization of energy consumption and thermal comfort by using interior light shelves in residential buildings, Renewable energy, 159 (2020) 736-755.

[30] P. Bakmohammadi and E. Noorzai, Optimization of the design of the primary school classrooms in terms of energy and daylight performance considering occupants' thermal and visual comfort, Energy Reports, 6 (2020) 1590-1607.

[31] N. Ziaee and R. Vakilinezhad, Multi-objective optimization of daylight performance and thermal comfort in classrooms with light-shelves: Case studies in Tehran and Sari, Iran, Energy and Buildings, 254 (2022) 111590.

[32] E. Breviglieri and P. De Castro, Quick Determination of Daylight and Irradiance in a room with lightshelf and its applications to a hot humid climate, in: Proceedings of Climate 2000 Conference, 1992, pp. 1-16, Brussels.

[33] F. C. Silva, A. Sophia, B. B. Santana, and P. Lúcio, Luminous performance of direct sun lighting systems in classrooms, pp. 9-12, 2003.

[34] E. L. Krüger and P. H. T. Zannin, Acoustic, thermal and luminous comfort in classrooms, Building and Environment, 39 (2004) 1055-1063.

[35] Y.-W. Lim, M. Z. Kandar, M. H. Ahmad, D. R. Ossen, and A. M. Abdullah, building façade design for daylighting quality in typical government office building, Building and Environment, 57 (2012) 194-204.

[36] H. Shen and A. Tzempelikos, Sensitivity analysis on daylighting and energy performance of perimeter offices with automated shading, Building and Environment, 59 (2013) 303-314.

[37] T. C. Y. Leung, P. Rajagopalan, and R. Fuller, Performance of a daylight guiding system in an office building, Solar Energy, 94 (2013) 253-265.

[38] U. Berardi and T. Wang, Daylighting in an atrium-type high performance house, Building and Environment, 76 (2014) 92-104.

[39] I. Acosta, M. Á. Campano, and J. F. Molina, Window design in architecture: Analysis of energy savings for lighting and visual comfort in residential spaces, Applied Energy, 168 (2016) 493-506.

[40] R. Delvaeye, W. Ryckaert, L. Stroobant, P. Hanselaer, R. Klein, and H. Breesch, Analysis of energy savings of three daylight control systems in a school building by means of monitoring, Energy and Buildings, 127 (2016) 969-979.

[41] M. L. Amundadottir, S. Rockcastle, M. Sarey Khanie, and M. Andersen, A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest and gaze behavior, Building and Environment, 113 (2017) 5-21.

[42] H. Lee, Performance evaluation of a light shelf with a solar module based on the solar module attachment area, Building and Environment, 159 (2019) 106161.

[43] S. Atti, S. Garat, M. Cools, S. Attia, S. Garat, and M. Cools, Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive façades, Building and Environment, 157 (2019) 268-276.

[44] K. H. Cheong, Y. H. Teo, J. M. Koh, U. R. Acharya, S. C. M. Yu, and S. C. Man Yu, A simulation-aided approach in improving thermal-visual comfort and power efficiency in buildings, Journal of Building Engineering, 27 (2020) 100936.

[45] M. Valitabar, A. Ghaffarian Hoseini, and S. Attia, Advanced control strategy to maximize view and control discomforting glare: a complex adaptive façade, Architectural Engineering and Design Management, 18 (2022) 829-849, 2022.

[46] A. Norouziasas, A. Tabadkani, R. Rahif, M. Amer, D.V. Dijk, H. Lamy, and S. Attia, Implementation of ISO/DIS 52016-3 for adaptive façades: A case study of an office building, Building and Environment, 235 (2023) 110195.

[47] E. Naderi, B. Sajadi, M. A. Behabadi, and E. Naderi, Multi-objective simulation-based optimization of controlled blind specifications to reduce energy consumption, and thermal and visual discomfort: Case studies in Iran, Building and Environment, 169 (2020) 106570.

[48] A. Nakhaee Sharif, S. Keshavarz Saleh, S. Afzal, N. Shoja Razavi, M. Fadaei Nasab, and S. Kadaei, Evaluating and Identifying Climatic Design Features in Traditional Iranian Architecture for Energy Saving (Case Study of Residential Architecture in Northwest of Iran), Complexity, 3 (2022) 1-12.

[49] Iranian National Building Code, Part 19: Energy Conservation, Ministry of Roads and Urban Development, 2020, Iran.

[50] ANSI/ASHRAE, ANSI/ASHRAE/IES Standard 90.1-2010 Performance Rating Method Reference Manual, 2016.

[51] P. Hoseinzadeh, M. Khalaji Asadi, S. Heidari, M. Khalatbari, R. Saidur, K. Haghighatnejad, and H. Sangin, Energy performance of building integrated photovoltaic high-rise building: Case study, Tehran, Iran, Energy and Building, 235 (2021) 110707.

[52] S. Liaison et al., ASHRAE STANDARD: Thermal Environmental Conditions for Human Occupancy, 2004.

[53] USDOE, Input Output Reference, Encycl. Ref. to EnergyPlus Input Output, 2019.

[54] M. Ghasri, M. Maghrebi, T. H. Rashidi, and S. T. Waller, Hazard-based model for concrete pouring duration using construction site and supply chain parameters, Automation in Construction, 71 (2016) 283-293.

[55] M. C. Peel, B. L. Finlayson, and T. A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrology and Earth System Sciences, 11 (2007) 1633-1644.

[56] NOVEDGE: Rhino 6 For Windows and Mac, 2022.

[57] M. Talaei, M. Mahdavinejad, R. Azari, A. Prieto, and H. Sangin, Multi-objective optimization of building-integrated microalgae photobioreactors for energy and daylighting performance, Journal of Building Engineering, 42 (2021) 102832, 2021.

[58] C. Sun, Q. Liu, and Y. Han, Many-objective optimization design of a public building for energy, daylighting and cost performance improvement, Applied Science, 10 (2020) 1-24.

[59] M. Kim, T. Hiroyasu, M. Miki, and S. Watanabe, SPEA2+: Improving the Performance of the Strength Pareto Evolutionary Algorithm 2, in: Parallel Problem Solving from Nature, 2004, pp. 742-751, UK.

[60] ISO, ISO 7730: Ergonomics of the Thermal Environment Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, International Organization for Standardization, Geneva, 2005.

[61] A. S. of H. R. and A.-C. Engineers, Thermal environmental conditions for human occupancy, 7 (2017) 60.

[62] A. Faraji, M. Rashidi, F. Rezaei, and E. Sorooshnia, Determining Appropriate Thermal Comfort Period based on PET and PMV using the RayMan Model: A Case Study in the Subtropical City of Sari, Architectural Engineering & Urban Planning, 32 (2022) 1-18.

[63] A. Yüksel, M. Arici, M. Krajcik, M. Civan, and H. Karabay, A review on thermal comfort, indoor air quality and energy consumption in temples, Journal of Building Engineering journal, 35 (2021) 102013.

[64] A. Faraji, M. Rashidi, F. Rezaei, and P. Rahnamayiezekavat, A Meta-Synthesis Review of Occupant Comfort Assessment in Buildings (2002-2022), Sustainability, 15 (2023) 4303.

[65] A. Faraji, M. Rashidi, F. Rezaei, and P. Rahnamayiezekavat, A Meta-Synthesis Review of Occupant Comfort Assessment in Buildings (2002-2022), Sustainability, 15 (2023) 4303.

[66] S. Zhang, W. He, D. Chen, J. Chu, H. Fan, and X. Duan, Thermal comfort analysis based on PMV/PPD in cabins of manned submersibles, Building Environment, 148 (2019) 668-676.

[67] K. Steemers, Daylighting design: Enhancing energy efficiency and visual quality, Renewable Energy, 5 (1994) 950-958.

[68] J. Y. Suk, Luminance and vertical eye illuminance thresholds for occupants' visual comfort in daylit office environments, Building Environment, 148 (2019) 107-115, 2019.

[69] S. Carlucci, F. Causone, F. De Rosa, L. Pagliano, F. De Rosa, and L. Pagliano, A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design, Renewable and Sustainable Energy Reviews, 47 (2015) 1016-1033.

[70] A. Faraji, F. Rezaei, P. Rahnamayiezekavat, M. Rashidi, and H. Soleimani, Subjective and Simulation-Based Analysis of Discomfort Glare Metrics in Office Buildings with Light Shelf Systems, Sustainability, 15 (2023) 11885.

[71] Rea Mark Stanley and Illuminating Engineering Society of North America, The Iesna Lighting Handbook: Reference & Application, New York: Illuminating Engineering Society of North America, 2000.

[72] J. Wienold and J. Christoffersen, Towards a new daylight glare rating, Lux Eur. Berlin, (2005) 157-161.

[73] A. Attia, S., Favoino, F., Loonen, R. C. G. M., Petrovski, A., & Monge-Barrio, Adaptive façades system assessment: An initial review Adaptive façades system assessment, in: 10th Conference on Advanced Building Skins, 2021, pp. 1275-1283, Switzerland.

[74] N. Delgarm, B. Sajadi, and S. Delgarm, Multi-objective optimization of building energy performance and indoor thermal comfort: A new method using artificial bee colony (ABC), Energy and Buildings, 131 (2016) 42-53.

[75] M. T. Aguilar-Carrasco, J. Díaz-Borrego, I. Acosta, M. Á. Campano, and S. Domínguez-Amarillo, Validation of lighting parametric workflow tools of Ladybug and Solemma using CIE test cases, Journal of Building Engineering, 64 (2023) 105608.

[76] A. A. S. Bahdad, S. F. S. Fadzil, and N. Taib, Optimization of daylight performance based on controllable light-shelf parameters using genetic algorithms in the tropical climate of Malaysia, Journal of Daylighting, 7 (2020) 122-136.

[77] M. Roshan and A. S. Barau, Assessing Anidolic Daylighting System for efficient daylight in open plan office in the tropics, Journal of Building Engineering, 8 (2016) 58-69.

[78] M. Pourahmadi, M.A. Khanmohamadi, and F. Mozafar, Windows optimization based on the glare performance in educational building of Iran hot and dry climate, Journal of Sustainable Architecture and Urban Design, 7 (2019) 113-128, 2019.

[79] F. Kharvari, an empirical validation of daylighting tools: Assessing radiance parameters and simulation settings in Ladybug and Honeybee against field measurements, Solar Energy, 207 (2020) 1021-1036.

[80] A. N. S. Institute, ANSI/ASHRAE Standard 140-2020: Method of Test for Evaluating Building Performance Simulation Software, pp. 404-636, 2021.

[81] A. N. S. Institute, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. ASHRAE, 2017.