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## Article

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## Research paper

# Optimization of the design of the primary school classrooms in terms of energy and daylight performance considering occupants' thermal and visual comfort

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## ABSTRACT

One of the top priorities in the building design process is minimizing energy consumption. Moreover, the level of occupants' comfort directly affects their learning ability. Therefore, this paper uses a multi-objective approach to optimize the architectural design features, including some newly examined ones, that define the geometry of a classroom. Furthermore, to create a practical methodology for minimizing lighting energy demand, we put the technique of dividing the class into independent, controllable lighting zones into practice for the first time. This research aims to introduce an optimized primary school classroom that meets both inhabitants' comfort needs and energy efficiency. For this, we first developed a parametric model using the Grasshopper plug-in for Rhino. Afterward, the environmental plug-ins of Honeybee and Ladybug were employed to evaluate energy performance and thermal comfort and find optimized solutions. The last step was assessing the occupants' visual comfort for each of these optimized solutions and selecting the final optimum designs. This two-phase optimization procedure has led to the reduction of total energy demand, up to 47.92 kWh/m<sup>2</sup>, and improvement of occupants' thermal and visual comfort. The results show that the proposed methodology can provide designers with a guideline for designing a sustainable classroom that fulfills their preferences as well as encouraging them to use innovative ways for energy conservation.

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## 1. Introduction

Architectural design is a complicated process which involves the integration of building, inhabitants' requirements, and environmental conditions (Golabchi et al., 2016; Gharouni Jafari et al., 2020). This process requires special attention since it plays a vital role in the development of sustainable buildings that satisfy occupants' demands, especially when it comes to educational buildings where architecture directly affects children's learning abilities. Therefore, school buildings should put a particular focus on occupant comfort as well as student and teacher performance, and at the same time, use the least possible amount of energy (Zhang et al., 2017; Lee et al., 2017).

Due to the devastations caused by Iran's eight years of war on one side and the rapid population growth of the 1980s on another side, constructing schools was needed to be carried out on a large scale and at the lowest possible cost. Such constructions were executed regardless of climate variations, usually with low-quality materials and construction methods. As a result, over one

hundred thousand schools were built with energy consumption of over 160 kWh/m<sup>2</sup>, which is about 2.5 times more than in developed countries with an average rate of 65 kWh/m<sup>2</sup> for their typical schools. Even with the high energy consumption, Post-Occupancy Evaluations (POE) report thermal dissatisfaction in classrooms (Tahsildoost and Zomorodian, 2015).

Daylighting is an integral aspect of indoor environmental quality assessment in buildings. The usage of daylight in the built environment not only causes the reduction of electrical energy, but also contributes to the creation of a space that has a positive influence on the health and well-being of building users. Several researchers have proved that daylight affects the educational experience of the students in the way that it increases productivity, improves human performance and has biological effects on the production of cortisol, a hormone that regulates the day-night cycles as well as the students' concentration (Mangkuto et al., 2019; Moreno and Labarca, 2015).

However, daylight can result in visual discomforts like glare and unwanted reflections and ultimately lead to the disruption of the thermal balance of rooms through overheating. For this reason, keeping the balance between the maximization of daylight harvesting and risk management of potential discomforts is the most ambitious challenge for designers (Tabadkani et al., 2018).

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## Nomenclature

ASE	Annual sun exposure, %
$at_i$	Occurrence count of exceeding the illuminance threshold at the point $i$
AT( $i$ )	Function assigned to grid points
CEUI	Cooling energy use intensity, kWh/m <sup>2</sup>
CTR	Annual thermal comfort ratio, %
DA	Daylight autonomy, %
DGP	Daylight glare probability index
$E$	Illuminance, lux
$EU_i$	Hourly energy demand, kWh
HEUI	Heating energy use intensity, kWh/m <sup>2</sup>
$i$	Point belonging to the calculation grid
$L$	Luminance, cd/m <sup>2</sup>
LEUI	Lighting energy use intensity, kWh/m <sup>2</sup>
$M$	Conditioning area, m <sup>2</sup>
$N$	Number of grid points
$N_h$	Annual heating hours
$N_c$	Annual cooling hours
$N_l$	Annual lighting hours
$P$	Position index
$q$	Total hour
$t$	Time (hour), h
$T$	Indoor operating temperature, °C
$T_{lower}$	Lower limits of the thermal comfort zone, °C
$T_{upper}$	Upper limits of the thermal comfort zone, °C
$T_i$	Annual absolute hour threshold
$T_c$	Indoor comfort temperature, °C
$T_r$	Outdoor reference temperature, °C
TEUI	Thermal energy use intensity, kWh/m <sup>2</sup>
UDI	Useful daylight illuminance, %
$wf$	Weighting factor
WWR	Window-to-wall Ratio, %
$\omega$	Solid angle, rad

Throughout the world, schools are first and foremost places for socialization, opening up to the world, acquiring knowledge: three fundamental principles for becoming a competent citizen of tomorrow's world. Since it has been scientifically proven that the lack of comfort has negative consequences on pupils' concentration and learning, comprehensive studies that take into account the meteorological parameters of the construction site, are needed before embarking on the construction phase. So, the most suitable design in terms of geometry and building orientation is determined (Trachte and De Herde, 2015).

Although in recent years, the quality of construction and school design in Iran has been enhanced, most schools in existence have built without consideration for occupants' thermal comfort. The leading cause is the lack of proper design guidelines for creating comfortable and healthy indoor environments in Iranian schools (Zahiri et al., 2011).

Using retrofitting methods after completion of the building project is inefficient and complicated. By contrast, it has been proven that it is more effective and economical to work with the optimized solutions obtained by algorithm-based optimization to achieve the ideal design (Sun et al., 2015). SPEA-2 is the improved version of Strength Pareto Evolutionary Algorithm (SPEA)

and it is one of the most important multi-objective evolutionary algorithms that use elitism approach. Consequently, in this paper, multi-objective optimization with the use of the SPEA-2 algorithm has been performed (Chołodowicz and Orłowski, 2016). Afterward, the optimum designs were selected on the Pareto front.

The objective of the paper is to introduce a beneficial layout for designing primary school classrooms in Tehran, according to the climate conditions and with the purpose of meeting both energy efficiency and occupants' satisfaction. Also, for providing more comfort while consuming less energy, the method of considering several lighting zones has been employed for the first time. This means that for each zone, the illuminance levels are adjusted according to the users' main specific task. Furthermore, the wall inclination angle has been examined as one of the variables of the optimization process. From a more general perspective, this research is aimed to remind architects and designers of the importance of user comfort along with reducing energy consumption as the essential sustainable design principles that are beneficial to humans and the environment in which they live. Developing the design process according to the principles of sustainability significantly reduces the costs throughout the entire life cycle of the building (Abbasi et al., 2020; Noorzai and Golabchi, 2020) and, ultimately, contributes to the construction of cities and buildings in a green and sustainable way (Trachte and De Herde, 2015).

## 2. Literature review and background

The most crucial architectural design stage is the early design phase, when most of the critical decisions are made and the largest impacts on building performance and occupant comfort are set (Taghizade et al., 2019; Konis et al., 2016). Hopefully, nowadays, simulation software programs that are powerful tools for studying the environmental performance of buildings, have become widely available and specialized. Moreover, weather data for most cities are gathered inside the weather files that are accessible to everyone. Hence, utilizing computer-simulation methods for design decision-making, especially in a country like Iran where there is a lack of guidelines for sustainable design, enables architects to comprehensively explore different solutions in an efficient manner, and drive the design towards optimized alternatives in the initial design stages (Touloupaki and Theodosiou, 2017; Zahiri et al., 2011; Gharouni Jafari et al., 2014; Noorzai, 2020).

### 2.1. Parametric design

W. Jabi defined Parametric Design as "A process based on algorithm thinking that enables the expression of parameters and results that, together, define, encode and clarify the relationship between design intent and design response" (Jabi, 2013; Touloupaki and Theodosiou, 2017). In the general architectural design, all design aspects can be considered as parameters, such as location, orientation, shape, and so on. In the conventional way of design, once an initial model has been created, if the designer wants to change any parameter, the whole process has to be repeated. Therefore, the examination of all the possible design alternatives to find the optimum solutions, without the use of parametric design, is time-consuming and complicated. As expected, the larger the project is, the more complex and unpredictable these relations get, to the extent that it is not feasible to analyze the project data without the help of parametric modeling software programs. It is only through parametric design that various design solutions can be found by using algorithmic methods, in response to the architectural design difficulties. That

is how the ambitious long-term goal of generating creative solutions in the design process is now achievable for ideologist architects (Eltaweel and Su, 2017; Touloupaki and Theodosiou, 2017).

## 2.2. Optimization of daylight, energy consumption and occupant comfort

In general, the utilized metrics in this work fall into three main categories. The first group includes functions that are related to daylighting and visual comfort. The second group involves energy consumption and the third group deals with occupants' thermal comfort.

### 2.2.1. Daylight performance and visual comfort

Many researches demonstrate that natural daylight utilization decreases the electric lighting and, more importantly, increases the health and productivity of the users. However, the amount of daylight entering the room should not exceed the limit where it would cause discomfort for occupants. Having this in mind, the evaluation of the amount of light would be grounded on the pragmatic factors below:

– *Useful Daylight Illuminance (UDI)*: This indicator is the annual time fraction that indoor horizontal daylight illuminance at a given test point reaches in a given domain, and it was proposed by Nabil and Mardaljevic in 2005. UDI contains lower and upper thresholds and an acceptable range as  $UDI_{underlit}$ ,  $UDI_{overlit}$  and  $UDI_{useful}$  respectively.

$$\left\{ \begin{array}{l} UDI = \frac{\sum_i (w_{f_i} \cdot t_i)}{\sum_i t_i} \in [0, 1] \\ UDI_{Overall} \text{ with } w_{f_i} = \begin{cases} 1 & \text{if } E_{Daylight} > E_{Upper \text{ limit}} \\ 0 & \text{if } E_{Daylight} \leq E_{Upper \text{ limit}} \end{cases} \\ UDI_{Useful} \text{ with } w_{f_i} = \begin{cases} 1 & \text{if } E_{Lower \text{ limit}} \leq E_{Daylight} \leq E_{Upper \text{ limit}} \\ 0 & \text{if } E_{Daylight} < E_{Lower \text{ limit}} \vee E_{Daylight} > E_{Upper \text{ limit}} \end{cases} \\ UDI_{Underlit} \text{ with } w_{f_i} = \begin{cases} 1 & \text{if } E_{Daylight} < E_{Lower \text{ limit}} \\ 0 & \text{if } E_{Daylight} \geq E_{Lower \text{ limit}} \end{cases} \end{array} \right. \quad (1)$$

where  $t_i$  is each occupied hour in a year, h;

$E_{Daylight}$  is the horizontal illuminance at a given point due to the sole daylight, lux;

$w_{f_i}$  is a weighting factor depending on values of  $E_{Daylight}$ .

Carlucci et al. and Hafiz defined UDI as the illuminances that fall within the range 100–2000 lux based on data from comprehensive field studies of occupant behavior. The higher the UDI value between 100 and 2000 lux, the better the visual comfort (Carlucci et al., 2015; Hafiz, 2015; Tabadkani et al., 2019).

– *Daylight Autonomy (DA)*: This is signified as a percentage of annual daytime hours that a given point in a space is above a specified illuminance level. This metric has been suggested

$$DA = \frac{\sum_i (w_{f_i} \cdot t_i)}{\sum_i t_i} \in [0, 1] \quad (2)$$

with  $w_{f_i} = \begin{cases} 1 & \text{if } E_{Daylight} \geq E_{limit} \\ 0 & \text{if } E_{Daylight} < E_{limit} \end{cases}$

by Reinhart and Walkenhorst in 2001.

where  $E_{limit}$  is the illuminance limit value, lux.

The level of illuminance is specified by any reference document for lighting such as the IESNA lighting Handbook and is defined as the amount of daylight illuminance required for that

specific task over the occupied times of the year (Alhagla et al., 2019; Tabadkani et al., 2019; Carlucci et al., 2015).

– *Annual sun exposure (ASE)*: It is the ratio of analyzed space that receives more than a certain amount of direct sunlight in a number of specific hours of the year. Both factors determination (number of hours and amount of radiation) in the index definition is required. Illuminating Engineering Society (IES) recommendation is  $ASE_{1000,250h}$ , which is the percentage of space in which in at least 250 occupied hours per year, the direct exposure of the sun is more than 1000 lux.  $ASE_{1000,250h}$  has been proposed by the Illumination Engineering Society of North America (IESNA), as one of the codified metrics in LEED v4 and must not exceed 10% of floor area (Pilechiha et al., 2020; Tabadkani et al., 2018; Futrell et al., 2015a,b; IESNA, 2012).

If we assume a grid of  $N$  points, and assign a function  $AT(i)$  whose value becomes one for every point  $i$  in the grid getting the minimum required illuminance for more than the given

$$ASE = \frac{\sum_{i=1}^N AT(i)}{N} \text{ with } AT(i) = \begin{cases} 1 & \text{if } at_i \geq T_i \\ 0 & \text{if } at_i < T_i \end{cases} \quad (3)$$

fraction of total occupancy time, ASE can be represented as where  $at_i$  is the occurrence count of exceeding the ASE illuminance threshold at the point  $i$  and  $T_i$  represents the annual absolute hour threshold (Pilechiha et al., 2020).

– *Daylight glare probability (DGP)*: It is the percent of people who are irritated by the level of disturbing glare, and it has been suggested by Wienold and Christofferson in 2006. Its formulation is

$$DGP = 5.87 \cdot 10^{-5} E_v + 0.098 \cdot \log_{10} \left[ 1 + \sum_{i=1}^n \left( \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2} \right) \right] + 0.16 \quad (4)$$

where  $E_v$  is the vertical eye illuminance produced by the light source, lux;

$L_{s,i}$  is the luminance of the source, cd/m<sup>2</sup>;

$\omega_{s,i}$  the solid angle of the source seen by an observer, rad;

$P$  is the position index, which expresses the change in experienced discomfort glare relative to the angular displacement of the source (azimuth and elevation) from the observer's line of sight.

Based on Eq. (4), the comfort criteria of glare are proposed by four main domains as tabulated in Table 1 (Carlucci et al., 2015; Tabadkani et al., 2018).

It is notable that because DA has no upper threshold for illuminance, it does not capture whether a design is over-illuminated, and therefore, possibly visually uncomfortable. Unlike other daylight metrics, UDI's "target range" of illuminance captures the daylight sufficiency and visual comfort of a design solution because values above the upper threshold are likely to cause visual discomfort/glare. Consequently, UDI is selected as the principal measure of daylighting performance because a good daylighting solution meets both the illuminance and visual comfort requirements of occupants. UDI is an excellent indicator of both (Futrell et al., 2015a,b). Also, since  $ASE_{1000,250h}$  is evaluated on horizontal (floor or work) plane only, an additional metric calculated through the observer's field of view is also needed to represent the risk of visual discomfort better. That is why it is recommended to employ the daylight glare probability (DGP) for daylighting cases (Mangkuto et al., 2019). Henceforth, in the present study, the UDI, ASE, and DGP are considered as the main indices to assess visual comfort.

### 2.2.2. Energy performance

This study aims to reduce annual thermal need along with the yearly electric lighting energy demand. For thermal performance, a heating or cooling load is defined as the amount of



**Table 1**  
Glare comfort criteria.

Daylight glare probability	Glare comfort
$DGP < 0.35$	Imperceptible glare
$0.35 < DGP < 0.4$	Perceptible glare
$0.4 < DGP < 0.45$	Disturbing glare
$0.45 < DGP$	Intolerable glare

heat required to be added to or removed from the room air mass to maintain the room air mass temperature at the thermostat setpoint temperature. Generally, for thermal evaluation, the sum of annual hourly heating loads and annual hourly cooling loads are used (Futrell et al., 2015a,b). Likewise, in this paper, thermal performance assessment is based on the annual thermal energy use intensity (TEUI), which is the sum of cooling energy use intensity (CEUI) and heating energy use intensity (HEUI). Similar to CEUI and HEUI, the lighting energy use

$$HEUI = \sum_{i=1}^{i=N_h} EU_{hi}/M \quad (5)$$

$$CEUI = \sum_{i=1}^{i=N_c} EU_{ci}/M \quad (6)$$

$$TEUI = HEUI + CEUI \quad (7)$$

intensity (LEUI), represented in Eq. (8), is used in this study.

$$LEUI = \sum_{i=1}^{i=N_l} EU_{li}/M \quad (8)$$

$EU_i$  is hourly energy demand, kWh;

$N_h$  is annual heating hours;

$N_c$  is annual cooling hours;

$N_l$  is annual lighting hours;

$M$  is the conditioning area, m<sup>2</sup>.

### 2.2.3. Thermal comfort

Comfort has a significant role in how people perceive a building, behave in the built environment and the amount of energy they consume daily. As a result, it can be concluded that comfort is not a product produced by the building, but it is a purpose that residents are willing to achieve (Nicol and Stevenson, 2013; Shove, 2003).

To accomplish this goal, providing comfort, whether from visual or thermal perspective, was considered in this article. Visual comfort and its related evaluation metrics have been mentioned previously and, in the following, the selected technique for assessing thermal comfort in this research is explained:

“Thermal comfort” is the term for describing a satisfactory, stress-free thermal environment in buildings and, thus, is a socially defined notion demonstrated by norms and expectations (Nicol and Roaf, 2017).

The Primary standards of thermal comfort that were developed (such as the primary form of ASHRAE Standard 55) specifically concentrated on the heat balance models which assume that thermal comfort is achieved if the body temperature can be held in a narrow range, skin moisture is low and physiological effort of regulation is minimized (ASHRAE, 2005). In these models, environmental factors (temperature, thermal radiation, humidity, and air velocity) and personal factors (activity and clothing) were taken into account as influential factors for thermal comfort. Nonetheless, soon it became clear that amendments needed to be done since occupant behavior was different from what the Standards predicted. After hundreds of field studies in which people in naturally ventilated buildings were asked about how comfortable they were, adaptive thermal comfort standards were established.

Results showed that users tended to adapt themselves to the monthly mean temperature and would be comfortable in buildings so long as the building temperature remained around a value close to that monthly mean. In fact, the adaptive thermal comfort model concerns behavioral reactions of residents to create suitable thermal conditions in addition to the fact that comfort is affected by outdoor environmental conditions of the region (de Dear and Brager, 1998). Based on ASHRAE Standard 55–2010 (ASHRAE, 2010), this model uses the relationship between the indoor comfort temperature and the outdoor temperature to define acceptable zones for indoor temperature in naturally conditioned buildings (de Dear and Brager, 2002). The linear equations for

$$T_c = 0.31 \times T_r + 17.8 \text{ } ^\circ\text{C} \quad (9)$$

calculating the indoor comfort temperature can be written as:

$T_c$  is indoor comfort temperature, °C;

$T_r$  is the prevailing mean outdoor air temperature for a time period between the last 7–30 days before the day in question, °C. This equation can be used when the outdoor dry bulb temperature remains above 10 °C and below 33.5 °C (de Dear and Schiller Brager, 2001; Zhang et al., 2017; ASHRAE, 2010). Fig. 1 shows the comfort bandwidths derived from Eq. (9), based on 80% and 90% occupant acceptability ranges. Considering 90% acceptability, thermal comfort fluctuates within 2.5 °C on either side of neutral temperature (5 °C bandwidth). The upper and lower limits ( $T_{upper}$  and  $T_{lower}$ ) are calculated based on Eqs. (10) and (11).

$$T_{upper} = 0.31 \times T_r + 20.3 \text{ } ^\circ\text{C} \quad (10)$$

$$T_{lower} = 0.31 \times T_r + 15.3 \text{ } ^\circ\text{C} \quad (11)$$

Based on the adaptive model, the annual thermal comfort ratio (CTR, %) is used as a thermal comfort measure. The calculation formula is as follows

$$CTR = \sum_{i=1}^q \frac{w_{fi}}{q} \times 100/\% \quad (12)$$

$$\text{with } w_{fi} = \begin{cases} 1 & \text{if } T_{lower} \leq T \leq T_{upper} \\ 0 & \text{if } T < T_{lower} \text{ Or } > T_{upper} \end{cases}$$

where  $T$  is the indoor operating temperature, °C;

$q$  represents the total hour.

The adaptive model of thermal comfort is currently supported by Standards like the International Standard ASHRAE RP884 and the European Standard EN 15251. That is why in this research, this model was employed for analyzing occupant comfort (de Dear and Schiller Brager, 2001; Wang et al., 2020a,b; Serghides et al., 2017; de Dear and Brager, 1998).

### 2.2.4. Previous studies related to the current research

In recent years, multiple studies have worked on the optimization of daylight and energy performance. Zomorodian and Nasrollahi (2013) optimized a constructed base case school building in Iran, through running several simulations, and they proved that using efficient architectural strategies can have a significant effect on the reduction of energy demand. Qingsong and Fukuda (2016), with the combination of parametric design and genetic algorithm, presented the optimum window dimensions to maximize useful daylight and minimize the energy demand of an office building in China. Konis et al. (2016) introduced a workflow with the name of the Passive Performance Optimization Framework (PPOF), which was aimed to the optimization of the finalized design for reaching high energy and daylight performance building. This framework includes conducting parametric analysis by Grasshopper software and then applying multi-objective optimization with the assistance of the Octopus plugin. Touloupaki and Theodosiou (2017) proposed the use of parametric geometry

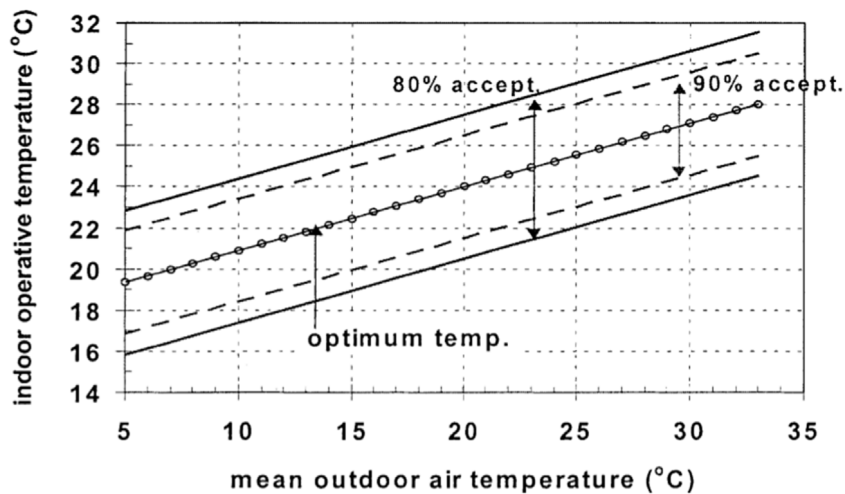


Fig. 1. Comfort bandwidths of ASHRAE 55–2010 (de Dear and Schiller Brager, 2001).

in the early stages of design and the implementation of optimization for finding the most suitable designs. Tabadkani et al. (2018) linked the parametric design to building visual environment and energy performance, and optimized the design parameters of an oriental responsive solar skin façade for an office unit in Tehran. Shahbazi et al. (2019) for improving daylight and energy performance, applied a multi-objective optimization approach to determine the optimum percentage of the window to wall ratio (*WWR*), number of windows, window height and still height for a building façade.

The number of researches in which such optimization is employed with an emphasis on occupants' visual and thermal comfort is limited, like the study that was carried out by Zhang et al. (2017). In this work, the optimization of daylight and energy is performed on three most common types of school building unit models, concerning inhabitants' comfort.

However, in this study, some of the influential parameters affecting the optimization task, such as the number of windows and consideration of multiple lighting zones, were not taken into account. Considering independent lighting zones enables designers to provide each zone with a suitable level of illuminance that is required by occupants while doing a specific task. It is noteworthy that none of the mentioned researches in the field of daylight optimization in classrooms, have noticed the importance of providing sufficient light levels for blackboard and they have deployed only one set of analysis points at work plane height (0.8 m above the floor). Moreover, due to the incredible technological advances occurring in the construction industry, now a wide variety of building forms are buildable. Consequently, during the concept design evolution, it is necessary to investigate the impact of perhaps more influential factors, other than elementary factors like length and width, which will determine the building form. One of these factors is the angle between the wall containing windows and the vertical direction. Angled walls are commonly used in many architectural designs presented by today's architects. In contrast, none of the previous studies on daylight optimization have examined the relation between the inclination angle of the wall that contains windows and the amount of daylight entering the room. In this research, this factor has been put into consideration as one of the design variables in the hope that designers pay proper attention to the influence of the selected angle on the amount of received daylight and accordingly on energy consumption. It is worth mentioning that most of the optimization researches have worked on existing

buildings to use the results for finding the efficient refurbishment strategies. However, prevention is always better than cure. So, it is recommended to accomplish necessary and sufficient studies during early project stages to guarantee the achievement of a sustainable and comfortable design for occupants, throughout the lifetime of the building.

### 3. Research methodology

#### 3.1. Required software programs for parametric design

The parametric design software was first revealed in 2008 and later developed by companies and software developers. One of the most commonly used software in this field is Grasshopper which is a graphical algorithm editor that serves as parametric modeling linked to Rhinoceros 3D and helps designers with no formal scripting background to generate parametric forms quickly (Lagios et al., 2010; Eltaweel and Su, 2017). Grasshopper can provide robust operation in the design and optimization procedure via developing an environmentally-conscious architectural design (Qingsong and Fukuda, 2016).

Therefore, in this research, three-dimensional parametric modeling of a primary school classroom was developed in Rhinoceros with the aid of the Grasshopper plug-in. Then, Grasshopper plug-ins, Ladybug, and Honeybee were used for the purpose of performing environmental analysis and calculating received daylight illuminance, energy consumption, visual and thermal comfort. It is worth noting that different glazing materials for windows were defined by the Berkeley lab WINDOW computer program. This software can calculate total window thermal performance indices (i.e., U-values, solar heat gain coefficients, shading coefficients, and visible transmittances). After that, the Octopus plug-in was used to apply multi-objective genetic algorithms and find optimal design solutions (Shahbazi et al., 2019; Eltaweel and Su, 2017). Finally, *DGP* and *ASE*, as indicators of visual comfort, were calculated for each of the selected solutions. In Fig. 2, a diagram of research methodology is provided.

#### 3.2. Classroom geometry and design variables

A typical classroom with a length of 10 m, a width of 7 m and, a height of 4 m (the dimensions that based on experience are usually used for a primary school classroom), was modeled in the

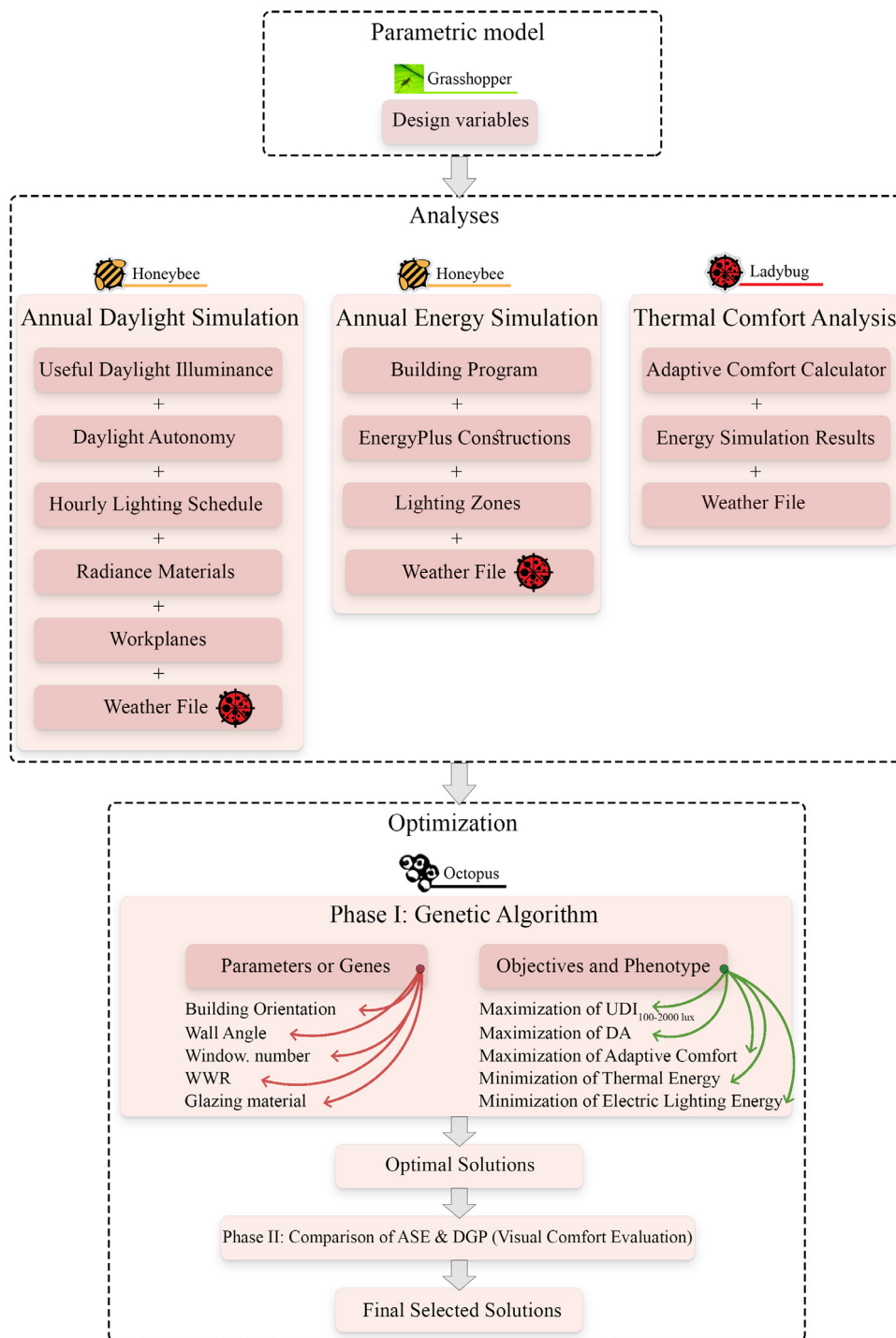


Fig. 2. Research methodology.

parametric 3D environment of Grasshopper and Rhinoceros, as shown in Fig. 3. To prevent the emergence of disturbing shadows caused by students' hands while writing, windows of the reference class were placed on the left side of students' tables. The wall on which windows are located, has been divided into three horizontal sections: a fixed part at the bottom; a dynamic part in the middle, with the distance of 0.8 m from floor and ceiling, and also capable of rotating in both clockwise and counterclockwise directions, within the limits of 0 to 30 degrees around the fixed bottom edge; another part at the top that is attached to the middle part and moves in a horizontal direction simultaneously

with the middle part changing rotation (Fig. 4). Afterward, a blackboard with dimensions of 4 m × 1 m, height of 0.8 m above the floor, and distance of 1.5 m from surrounding walls on the left and right side, was added to the model. It is also notable that the reference classroom was inspired by the proposed model on page 192 of the handbook concerning the IEA SHC Programme Task 47 Solar Renovation on Non-Residential Buildings (Trachte and De Herde, 2015).

Generally, building orientation, the angle between the wall containing windows, and the vertical direction and variables related to the design of windows (number of windows, WWR,

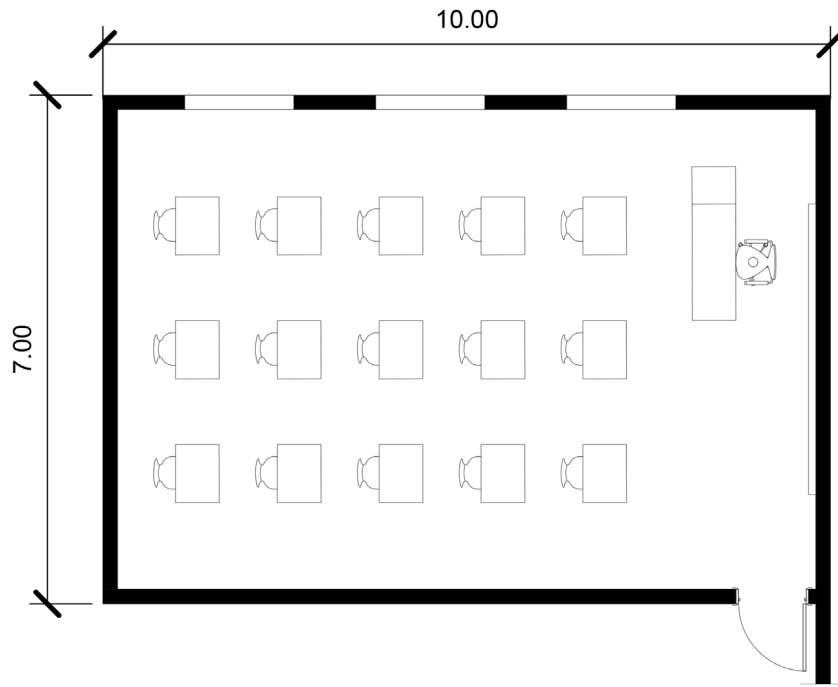


Fig. 3. Floor plan of the reference classroom.

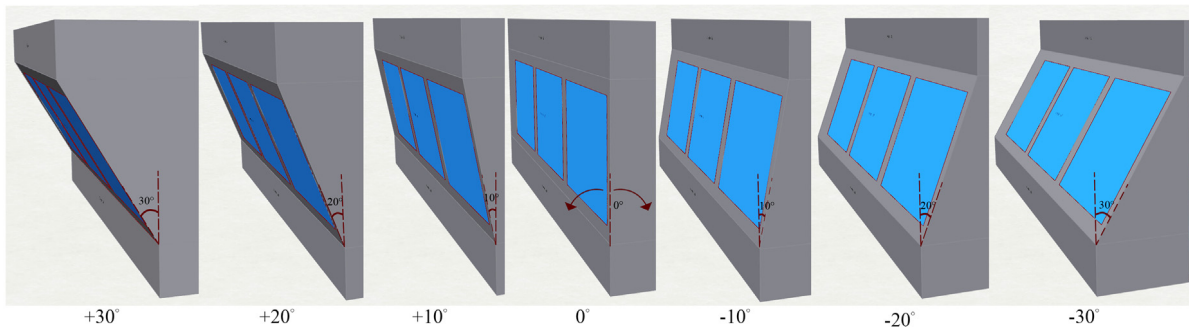


Fig. 4. Wall inclination angles.

Table 2  
Design parameters.

Variable	Attributes	No. of values
Building orientation	0, 45, 90, 135, 180, 225, 270, 315 (°)	8
Wall inclination angle	-30, -20, -10, 0, 10, 20, 30 (°)	7
Window. Number	1, 2, 3, 4, 5, 6, 7	7
WWR	20, 30, 40, 50, 60, 70, 80 (%)	7
Glazing material	0, 1, 2	3

Table 3  
Building program.

Attributes	Values
Project type	Medium classroom
Floor area	70 m <sup>2</sup>
Floor	Exterior floor
Zones program	Primary school classroom
Working hours	8 AM– 8 PM
Equipment load per area	7.6424 W/m <sup>2</sup>
Infiltration rate per area	0.0002 m <sup>3</sup> /s m <sup>2</sup>
Lighting density per area	11.8404 W/m <sup>2</sup>
Num. of people per area	0.0565 ppl/m <sup>2</sup>
Ventilation per area	0.0003 m <sup>3</sup> /s m <sup>2</sup>
Ventilation per person	0.0024 m <sup>3</sup> /s

and glazing material) were considered as design parameters utilized for the optimization process in this study. Table 2 presents simulation variables along with their values.

### 3.3. Climate data

For running the simulation, the Tehran-Mehrabad 407540 (ITMY) ZIP file was download from the EnergyPlus website and imported in the Ladybug plug-in (Fig. 5). According to the meteorological station statistics gathered by the International Exhibition of Tehran during 18 years, 10th July to 10th August is

the warmest month of the year, with an average temperature of 35.6 °C, and 10th January to 10th February is the coldest month of the year, with an average minimum temperature of -0.7 °C. It is necessary to pay enough attention to such information during the design stage to avoid the disruption of occupants' thermal comfort, for example, via maximizing daylight during the warmest months of the year.



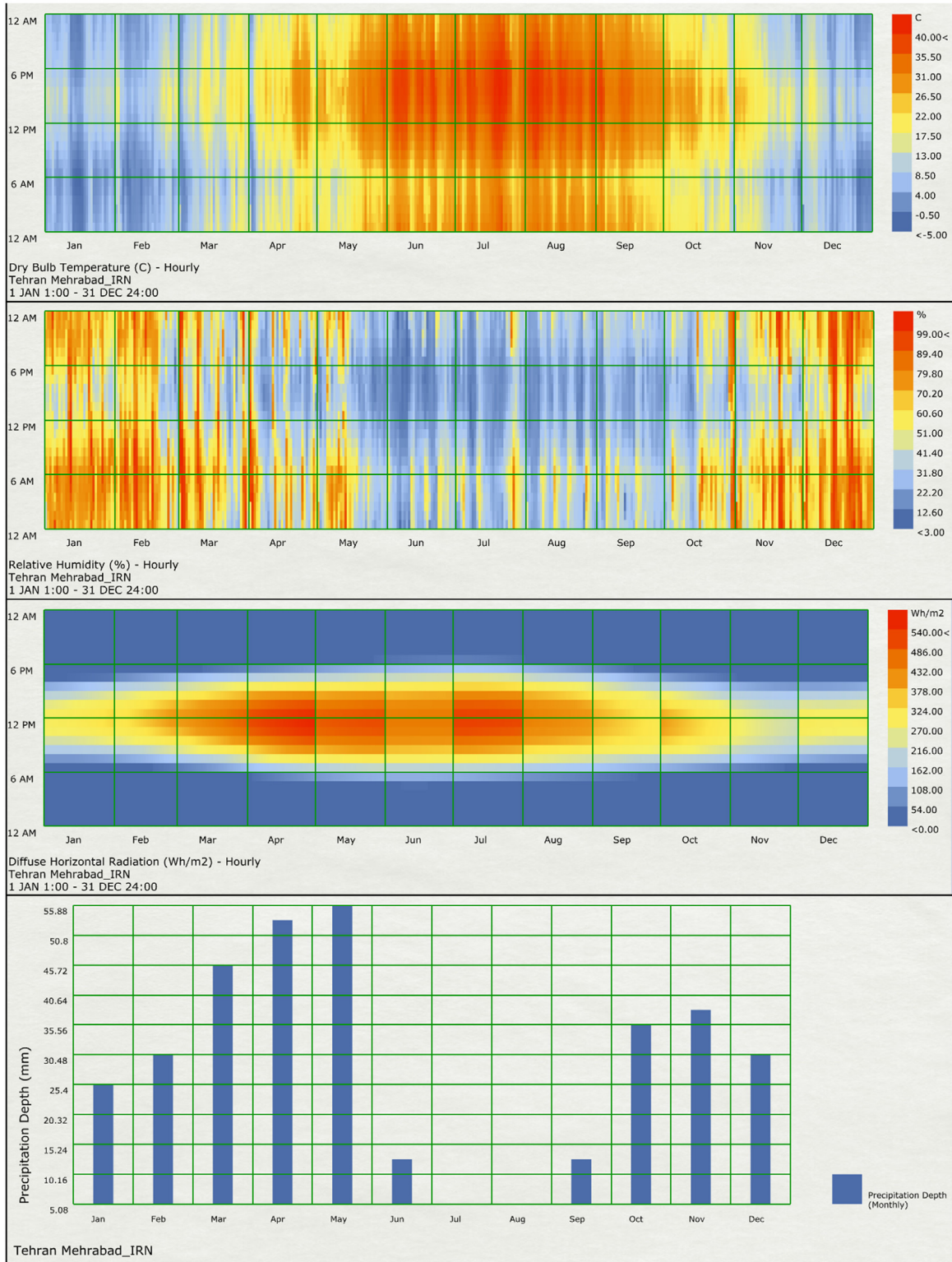


Fig. 5. Tehran monthly climate data.

### 3.4. Annual daylight simulation

#### 3.4.1. UDI and DA

After the completion of the modeling phase, annual daylight simulation was carried out by Honeybee plug-in, and UDI and DA

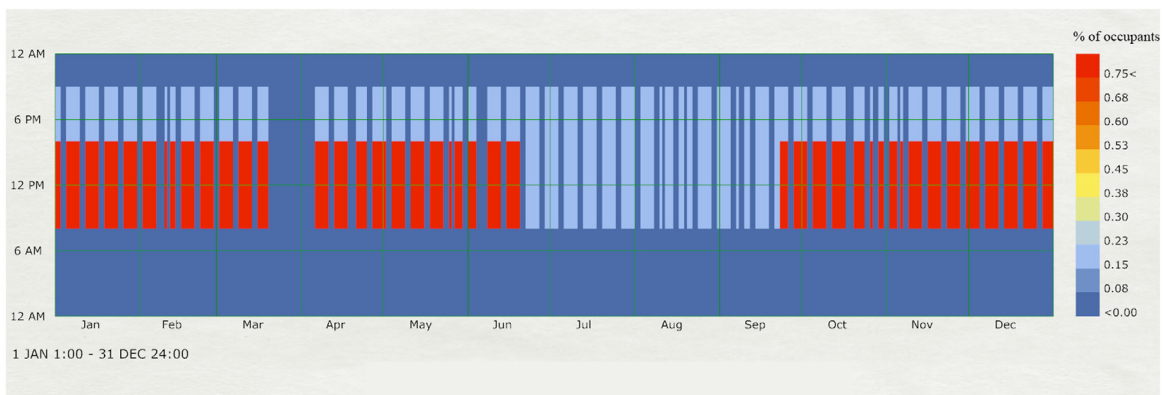
values were calculated. Based on the established values in valid international standards like IESNA, a minimum limit value of 300 lux is required for performing a simple task in an educational environment. Also, according to the first UDI definition, there is an upper limit of 2000 lux for illuminance value for the sake

**Table 4**  
Defined materials.

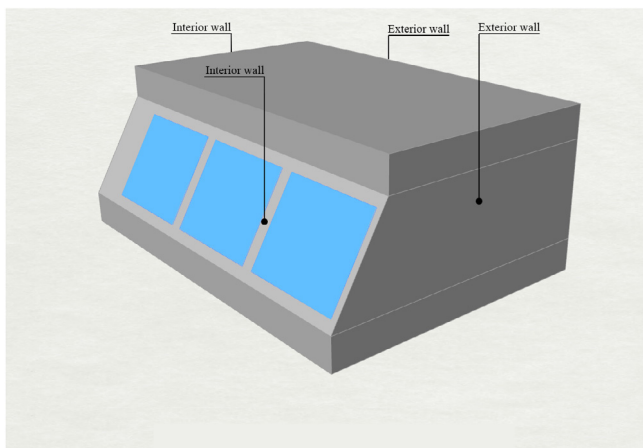
Attributes	Materials	U-value (W/(m <sup>2</sup> K))
Exterior floor	I02 50 mm insulation board + M15 200 mm heavyweight concrete	0.56
Exterior wall	ASHRAE 90.1-2010 EXTWALL MASS CLIMATEZONE 3: 1IN Stucco + 8IN CONCRETE HW RefBldg + Mass Wall + Insulation R-5.74 IP + 1/2IN Gypsum	0.78
Interior wall	G01a 19 mm gypsum board + F04 Wall air space resistance + G01a 19 mm gypsum board	2.58
Exterior roof	ASHRAE 90.1-2010 EXTROOF IEAD CLIMATEZONE 2-8: Roof Membrane + IEAD Roof Insulation R-19.72 IP + Metal Decking	0.28
Glazing	Single Clear (SHGC:0.861/ Index=2)	5.91
	Double Clear Air (SHGC:0.704/ Index=1)	2.70
	Triple Clear (SHGC:0.617/ Index=0)	1.74

**Table 5**  
Recommended light levels for the specific task which is done in each zone.

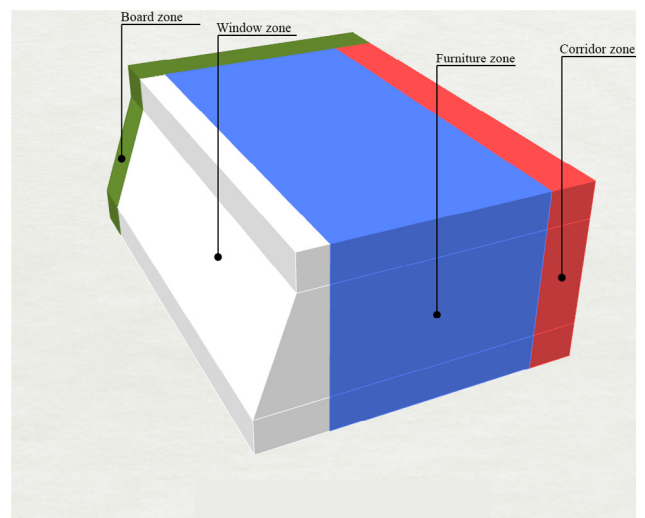
Zone	Attributed task		Standard illuminance	
	The teacher	The student	In the class	In general
Window zone	Paying attention to working students/ Talking to the students	Paying attention to the teacher/ Writing, reading, drawing, etc.	300 lux	300 lux
Furniture zone	Paying attention to working students/ Talking to the students	Paying attention to the teacher/ Writing, reading, drawing, etc.	300 lux	300 lux
Board zone	Writing on blackboard	Reading on blackboard	500 lux	300 lux
Corridor zone	Walking	Walking	50 lux	50 lux



**Fig. 6.** Annual occupancy chart for classroom.



**Fig. 7.** Definition of interior and exterior walls.



**Fig. 8.** Defined lighting zones.

of reducing the risk of glare. Hence, an illuminance threshold of 300 lux was considered for DA calculations (Moreno and Labarca, 2015).

#### 3.4.2. Occupancy schedule

Annual daylight simulation was conducted for Iranian school weekdays (from Saturday to Wednesday) from 8 am to 8 pm. It is also worth mentioning that Iranian school holidays, based on Persian Calendar 1397 that is almost equal with the period of 21st March 2018 to 20th March 2019, are taken into account as well. In Fig. 6, the approximate dates of Persian holidays can be perceived.

#### 3.4.3. Analysis grid

Daylight performance was simulated on two planes, and thus two different sets of analysis points were created: One grid of 0.5 m × 0.5 m at a working level height of 0.8 m, with 20 × 14 sensor points and another grid of 0.3 m × 0.3 m on the blackboard surface, with 20 × 14 sensor points.

#### 3.4.4. Materials

In the daylighting simulation process, custom Radiance materials were assigned to classroom surfaces. As shown in Fig. 7, two different sets of adjacent walls were defined: one set as interior (adiabatic) walls and another set as exterior ones.

### 3.5. Annual heating, cooling, and electric lighting energy demand simulation

#### 3.5.1. Building schedules

Honeybee has a library of default building programs using the OpenStudio's default schedules. In order to define energy simulation inputs including occupancy, activity, heating, cooling schedules, lighting power density, ventilation rates, equipment loads, etc., we extracted and utilized the present information inside the schedule of a primary school classroom as CSV files, categorized under default building programs presented by Honeybee (PrimarySchool::Classroom). Although working hours for each week were defined from Saturday to Wednesday, 8 am – 8 pm and also, Iranian school holidays were put into consideration as well. According to this schedule, the setpoint temperature for heating is set at 21 °C, and for cooling is at 24 °C. Also, the heating set-back is 16 °C, and the cooling set-back is 27 °C. In Table 3, defined values determining the building schedule, are listed, and in Fig. 6, the occupancy chart is presented for a whole year.

#### 3.5.2. HVAC

The HVAC system is selected to be the ideal loads air system in EnergyPlus, which is most suitable in the early design stage, considering the calculation time cost (Zhang et al., 2017).

#### 3.5.3. Materials

According to ASHRAE Standard 169–2013 (ASHRAE, 2013), the city of Tehran is located in climate zone 3B, assigned material for each surface was selected accordingly from the recommended materials offered by ASHRAE for climate zone 3. In Table 4, the properties of chosen materials have been introduced (ASHRAE, 2010).

Additionally, as already mentioned, three different types of glazing material were allocated to windows, with the assistance of LBNL Window software developed by Berkeley lab.

#### 3.5.4. Defining individually controllable lighting zones

For achieving both goals of minimizing the lighting energy demand and meeting users' visual comfort at the same time, the reference classroom was divided into four lighting zones, based on the proposed in the guidebook on IEA SHC Programme

Task 47 (Fig. 8). Given the users' main task in each zone, the required level of illuminance proposed by IESNA standards is set for every zone (Table 5). As a result, the target illuminance value was assumed to be 300 lux for the window zone and furniture zone, 500 lux for the board zone, and 50 lux for the corridor zone. Each zone is equipped with a dimmed lighting system and a daylight sensor that is placed in the center of the zone, at 0.8 m above the floor (work plane height). In each zone, the photocell dims the activated electric lights until the total illuminance levels (daylight and electric light) reaches the defined minimum illuminance threshold. In other words, if the amount of daylight exceeds the defined illuminance threshold for each zone, lights will be dimmed, thereby reducing the energy consumption (de Bruin-Hordijk and de Groot, 2007; Rea, 2000; Trachte and De Herde, 2015).

### 3.6. Thermal comfort

As mentioned earlier, the adaptive thermal comfort model was applied to evaluate occupants' thermal comfort. In Fig. 9, the adaptive chart for the city of Tehran is displayed with the help of Ladybug. Also, the indoor comfort boundary is marked based on the ASHRAE 55–2013 standard with the 90% acceptability limits.

### 3.7. Optimization process

As already stated, in this study, the main focus is on providing occupants' comfort along with minimizing total energy demand. For this reason, we used a two-phase optimization method. The first phase included the application of a multi-objective genetic algorithm. In the second phase, the visual comfort criteria for each of the selected solutions in the first phase were assessed and compared.

#### 3.7.1. First phase: multi-objective optimization

Genetic Algorithms (GA) are a specific category of evolutionary algorithms that utilize methods inspired by evolutionary biology such as inheritance, mutation, selection, and crossover to evolve a solution for general or particular problems. They have been proven to be a useful technique for addressing multi-objective design problems and calculate multiple performance criteria, finding close to optimal solutions within a short period (Mahdavejad and Mohammadi, 2016). In general, genetic algorithms are the most popular algorithms for optimizing building performance and have reliable results (Taghizade et al., 2019).

To perform the multi-objective optimization, Octopus plug-in, which uses a genetic algorithm, was employed. Octopus is based on SPEA-2, an improved multi-objective evolutionary algorithm that is both user-friendly and flexible enough to integrate into most design optimization processes. One of the advantages of using Octopus in comparison with other similar optimization tools in Grasshopper is the ability to define multiple objectives that can be evaluated simultaneously, which provides optimal solutions, presenting the best mode of objectives. This technique of optimization enables the examination of correlations between different objectives and provides a more comprehensive arrangement of outcomes compared to single-objective optimization analysis. The result, after several iterations and the elimination of unfit solutions, is a pool of optimized design alternatives that meet the objective function set. This plug-in is getting popular and has also been verified by recent research (Zhang et al., 2017; Shahbazi et al., 2019; Touloupaki and Theodosiou, 2017; Mahdavejad and Mohammadi, 2016).

– *Objective Functions:* To define the objective functions, we use the outputs of daylight and energy simulations which are the annual UDI, DA, thermal energy use intensity (TEUI), electric lighting



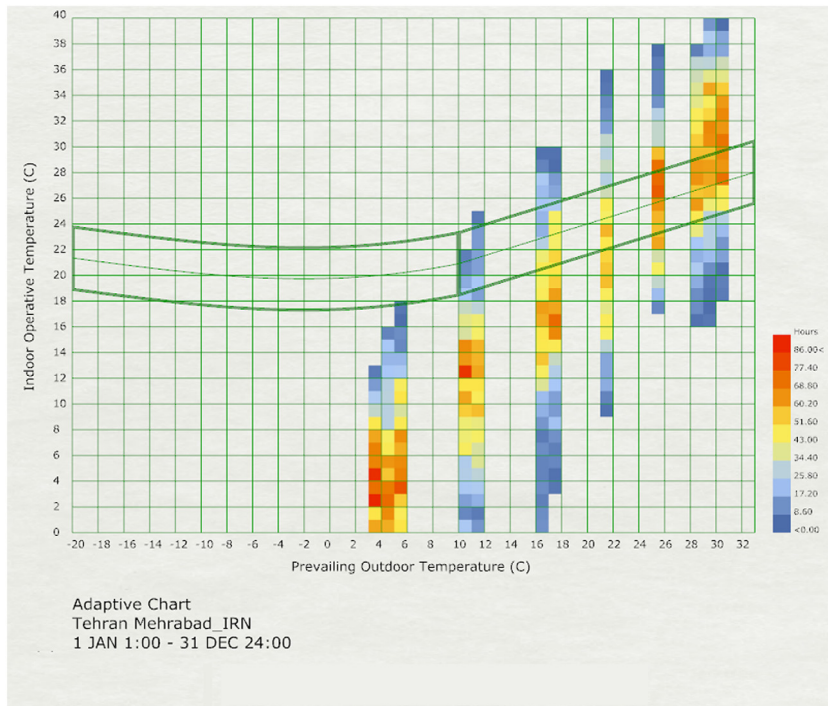


Fig. 9. Thermal adaptive chart of Tehran.

Table 6

Settings of the optimization algorithm.

Elitism	Mutation probability	Mutation rate	Crossover rate	Population size	Maximum generation
0.510	0.050	0.05000	0.800	100	20

energy use intensity ( $LEUI$ ), and occupant thermal comfort ( $CRT$ ). In

$$\begin{aligned}
 F_1: & \max (UDI_{100-2000} \text{ lux}) \\
 F_2: & \max (DA) \\
 F_3: & \min (TEUI) \\
 F_4: & \min (LEUI) \\
 F_5: & \max (CRT)
 \end{aligned} \tag{13}$$

conclusion, the optimization problem can be formulated as:

At first, we had included  $DGP$  into objective functions but due to this fact that the process of computing and calculating the image-based glare analysis for every hour of a whole year can take very long, for even one case let alone all the approximately 2800 design options, this technique is not applicable for many designers. So, instead, two separate phases are considered for selecting the optimal outcomes. Not only is this technique much less time-consuming, but also every designer can easily apply it with the use of a typical PC or laptop. For example, the optimization process of our study was carried out on a computer equipped with a Core i9-7900x processor and 16 GB of RAM, and the optimization process took approximately three days.

Moreover, the reason for including  $DA$  as a supplementary objective function is to challenge whether the benefits of maximizing this metric can really outweigh its drawbacks when inhabitants' visual comfort is taken into account, especially in countries like Iran, where experience shows that many schools in Iran would probably refuse to install shading devices, either because

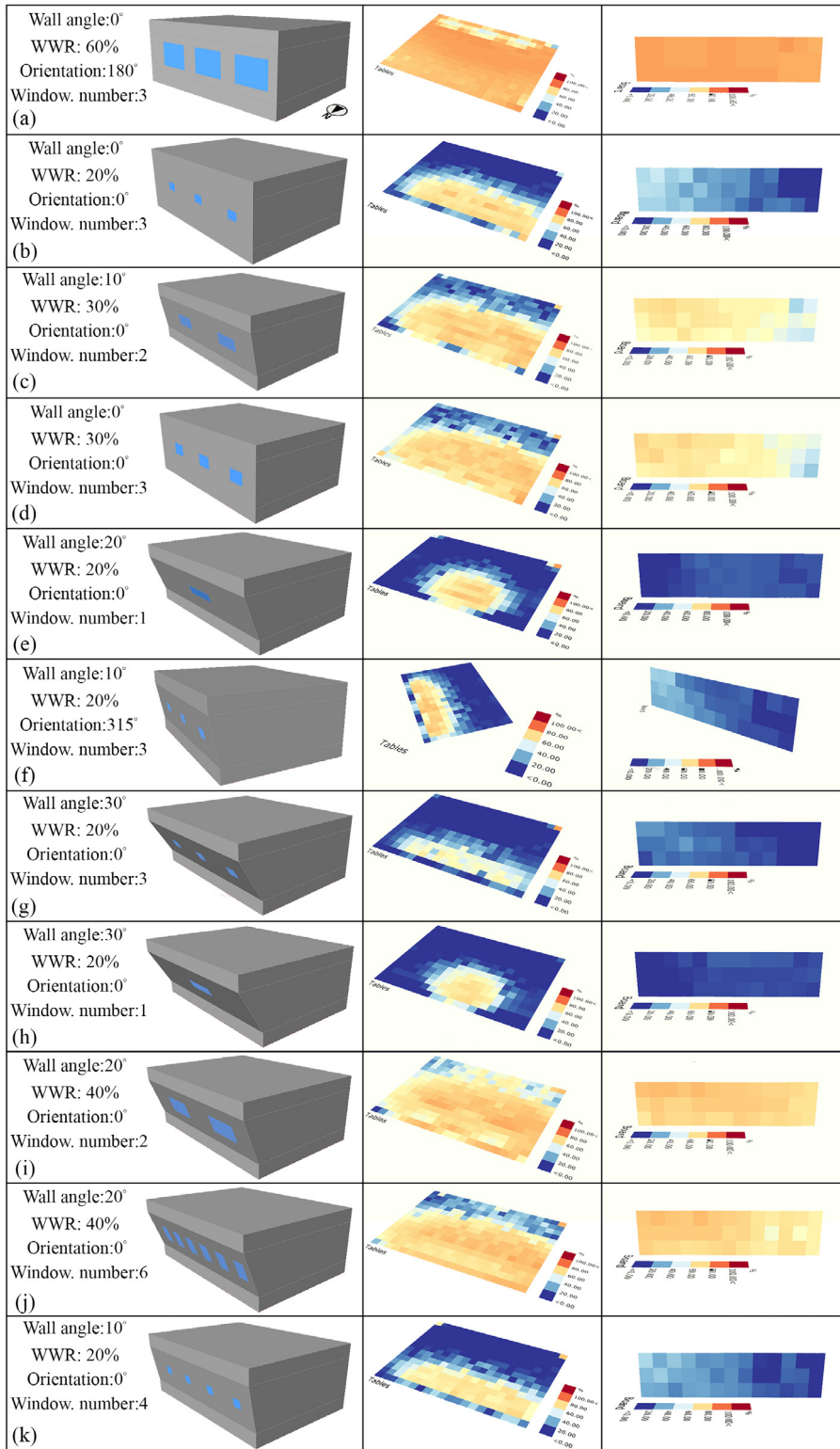
of not having enough budget or considering them as a useless extra expense. After analyzing hundreds of different design options, we have concluded that in most cases without a shading system, high amounts of  $DA$  can disturb visual comfort. This is a crucial factor that architects should pay attention to. Furthermore, in this paper, the method of dividing the class into independently controllable lighting zones is carried out for the first time. Since we wanted to carefully examine the relations between the lighting energy demand of all the defined zones and the amount of other metrics such as  $DA$ ,  $UDI$ , we considered them separately as individual objective functions.

It is also worth noting that the main reason behind considering two separate objective functions as electric lighting energy and thermal energy is to accurately analyze their fluctuations and changes individually, focusing on the effects of putting the method of defining controllable lighting zones into practice for the first time, on each of thermal and lighting energy.

– *Optimization settings:* The parameters of the optimization algorithm were set according to Table 6. The optimization procedure was carried out for one of the glazing materials, with consideration of 4 previously introduced variables. Also, since Octopus can only solve minimization problems,  $UDI$ ,  $DA$ , and  $CRT$  were multiplied by  $-1$ .

### 3.7.2. Second phase: assessing visual comfort

After selecting the optimum design solutions in the first phase, values of  $ASE$  and  $DGP$  that are considered as reliable indexes for assessing visual comfort in international standards like IESNA, were determined for each of the given solutions in the second phase. The process of calculating  $DGP$  and  $ASE$  value was implemented by Honeybee, which uses the most valid simulation tools, including Radiance, Daysim, and Evalglare. In order to compute  $DGP$ , a specific camera view at the observer's eye height (1.1 m height) was defined in the Rhino working environment. Then the resulted HDR image is used for vertical illuminance measurements. Afterward, the point-in-time glare analysis was done at

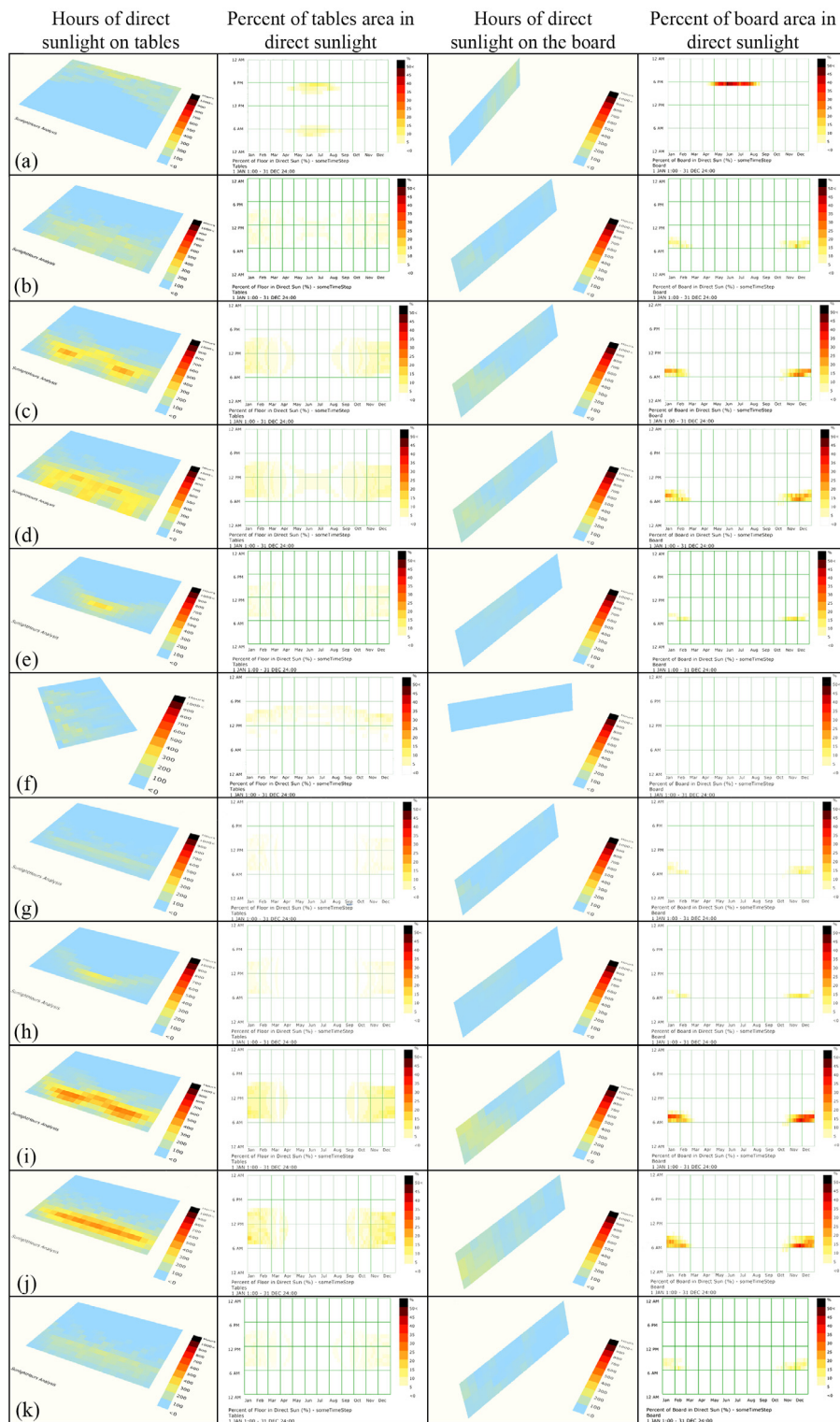


**Fig. 10.** UDI percentage on tables and blackboard: (a) base case, (b) 1st solution, (c) 2nd solution, (d) 3rd solution, (e) 4th solution, (f) 5th solution, (g) 6th solution, (h) 7th solution, (i) 8th solution, (j) 9th solution, (k) 10th solution.

12:00 pm of the winter solstice (21st of December), and then the annual glare analysis was conducted, in the way that *DGP* was computed for every hour of the defined occupancy schedule, during a whole year. Finally, all the *DGP* values for the sunlight hours were added together and divided by the total number of

sunlight hours during the year so that the average *DGP* was obtained during one year. Additionally, *ASE* was simulated using *Ladybug*. The last step was the comparison of *ASE* and *DGP* among the solutions and finding the best ones in terms of visual comfort performance.



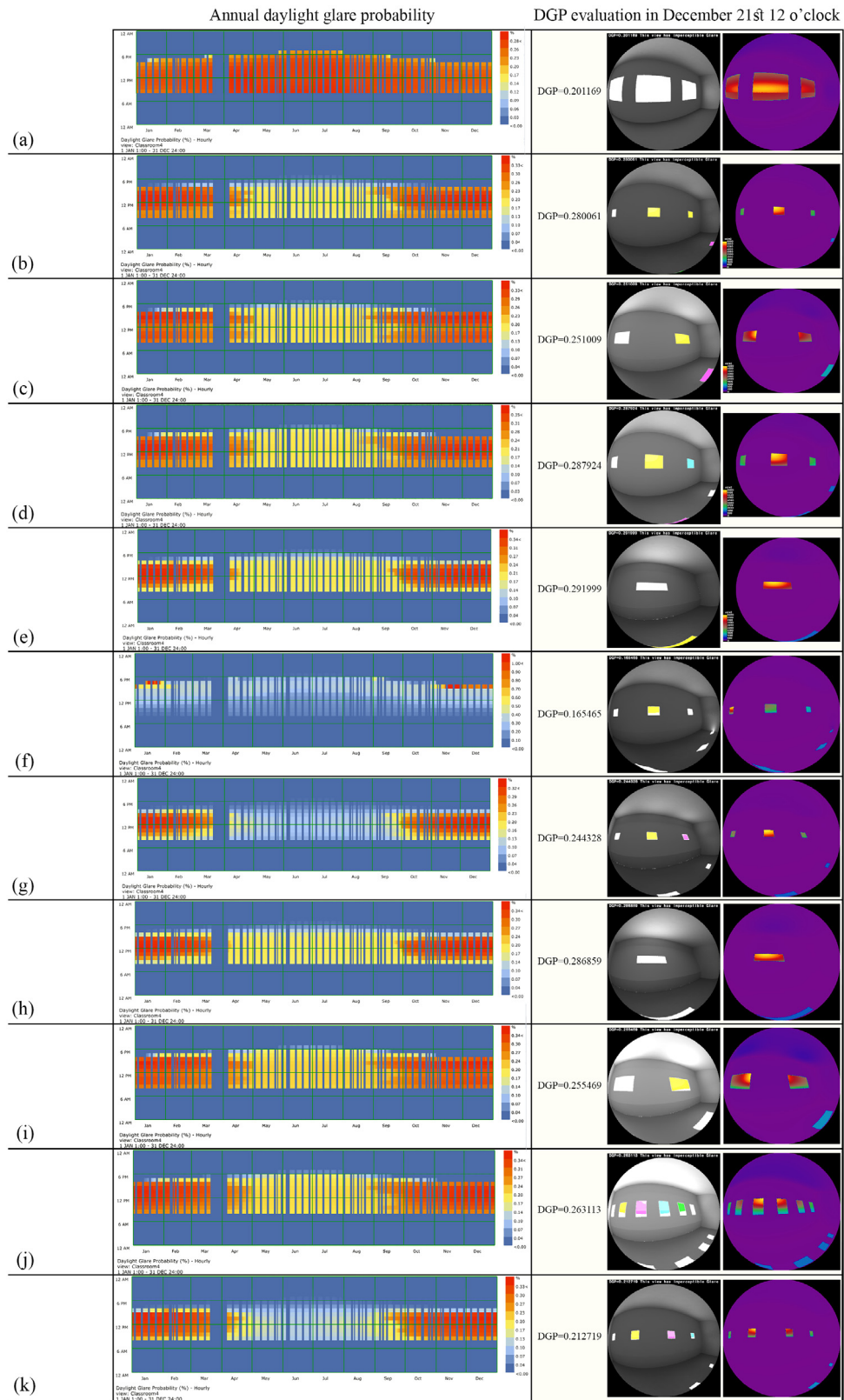


**Fig. 11.** Percentage of analyzed surfaces and number of hours in direct sunlight: (a) base case, (b) 1st solution, (c) 2nd solution, (d) 3rd solution, (e) 4th solution, (f) 5th solution, (g) 6th solution, (h) 7th solution, (i) 8th solution, (j) 9th solution, (k) 10th solution.

**4. Results**

The simulation loop ran for 20 generations and with 100 individual solutions for the third glazing material. The total number of approximately 2800 designs were compared with each other, and 10 of them were selected on Pareto front as optimal design solutions.

Because Tehran and on a larger scale, Iran is positioned in the northern hemisphere, the forms of the buildings are often elongated along the east–west axis with windows facing North. The reason is to prevent direct sunlight from entering the room so that the risk of discomfort glare is reduced since experience shows that many schools in Iran would probably refuse to install shading devices, either because of not having enough budget or



**Fig. 12.** DGP values: (a) base case, (b) 1st solution, (c) 2nd solution, (d) 3rd solution, (e) 4th solution, (f) 5th solution, (g) 6th solution, (h) 7th solution, (i) 8th solution, (j) 9th solution, (k) 10th solution.

considering them as a useless extra expense. As a result, the floor plan of the base case classroom was considered as shown in Fig. 3. The three-dimensional shape of the class is also considered to be

a simple box with three windows, each with the width of 2.3 m and the height of 1.86 m, on the northern wall; similar to the common design of the majority of classrooms in Tehran (Fig. 10).

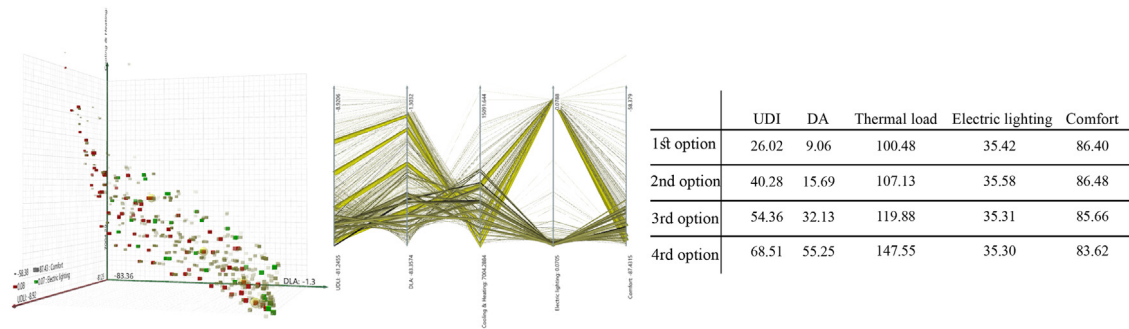


Fig. 13. Assessment and comparison of objective functions for 4 randomly selected options.

Table 7

Comparison of energy demands and thermal comfort before and after optimization.

Classroom designs	Glazing material	TEUI (kWh/m <sup>2</sup> )	LEUI (kWh/m <sup>2</sup> )	Total energy consumption (kWh/m <sup>2</sup> )	CTR (%)
Base case	Index=2	125.84	44.70	170.54	85.16
	Index=1	117.17	44.70	161.87	85.86
	Index=0	113.07	44.70	157.77	86.16
1st solution	Index=2	97.05	25.46	122.51	86.79
	Index=1	96.16	26.27	122.43	87.10
	Index=0	95.77	27.07	122.84	87.39
2nd solution	Index=2	98.33	24.03	122.36	86.34
	Index=1	96.74	24.29	121.03	86.71
	Index=0	96.08	24.54	120.62	86.95
3rd solution	Index=2	100.06	23.81	123.87	85.71
	Index=1	97.97	24.00	121.97	86.10
	Index=0	97.01	24.18	121.19	86.38
4th solution	Index=2	99.18	23.92	123.10	86.93
	Index=1	97.87	24.14	122.01	87.21
	Index=0	97.34	24.36	121.70	87.41
5th solution	Index=2	100.21	26.55	126.76	87.16
	Index=1	99.19	27.48	126.67	87.34
	Index=0	98.70	28.34	127.04	87.40
6th solution	Index=2	100.27	28.62	128.89	87.43
	Index=1	99.56	30.14	129.70	87.56
	Index=0	99.27	31.39	130.66	87.62
7th solution	Index=2	101.90	24.15	126.05	87.03
	Index=1	100.53	24.46	124.99	87.23
	Index=0	99.94	24.78	124.72	87.40
8th solution	Index=2	102.28	23.59	125.87	85.99
	Index=1	99.62	23.77	123.39	86.39
	Index=0	98.48	23.94	122.42	86.72
9th solution	Index=2	102.30	23.57	125.87	85.96
	Index=1	99.63	23.74	123.37	86.38
	Index=0	98.49	23.90	122.39	86.72
10th solution	Index=2	96.48	26.14	122.62	87.33
	Index=1	95.77	27.13	122.90	87.49
	Index=0	95.50	28.02	123.52	87.57

Subsequently, annual energy demand and received daylight were calculated for the base case. With comparing these amounts between the reference model and optimum selected solutions, designers can gain a better understanding of how an efficient building in terms of energy performance and occupants' comfort is achievable through choosing thoughtfully among various design options. It should be noted that the most influential criteria in the selection of the solutions were acquiring the highest thermal comfort percentage at the cost of the least possible amount of energy in the first place and receiving the largest percentage of  $UDI_{100-2000lux}$  and  $DA$  in the second place. As stated earlier, in order to keep the balance between the thermal energy demand and electric lighting energy demand, both of them were

considered as separate objective functions in the first phase of optimization process. However, in some cases, the difference between the numbers in each category was not significant enough to influence the selection of the best outcomes so, they were added up together and considered as one objective indicating the total energy consumption.

Tables 7 and 8, together with Figs. 10 to 12, are dedicated to comparing the values of objective functions, before and after optimization. In Table 7, values of the required annual heating, cooling, and lighting energy required for classroom plus thermal comfort percentage are presented. By comparing these numbers, it can be concluded that electric lighting energy demand for the base case and before the consideration of individually controllable lighting zones, was about 44.7 kWh/m<sup>2</sup> and after that, it has reduced to 23.07 kWh/m<sup>2</sup>. This reduction of 48% can be extremely beneficial for conserving the environment as well as decreasing overall costs. Among the introduced solutions, the 10th one with the total energy demand of 122.62 kWh/m<sup>2</sup> and thermal comfort of 87.33% had the best performance. Compared with the base case, this solution had a reduction of 18.56 kWh/m<sup>2</sup> in electric energy, 29.36 kWh/m<sup>2</sup> in thermal need, and 47.92 kWh/m<sup>2</sup> in the total energy consumption (electric lighting plus the amount of energy needed for heating and cooling) during a whole year. Moreover, thermal comfort increased by 2.17%.

In Table 8, daylight metrics for the base case and optimum solutions are calculated. As it can be seen, 8th and 9th design options, which have the largest  $WWR$ s among the solutions, also have the highest amount of  $UDI$ ,  $DA$ ,  $DGP$  and  $ASE$ . Additionally, the 10th one has the lowest amount of  $DGP$  and  $ASE$ , indicating a better condition for satisfying occupants' visual comfort (Tabadkani et al., 2018).

Fig. 10 Demonstrates that for almost all the optimum solutions building orientation is 0°, indicating that in Iran, buildings facing south are advantageous for thermal and daylighting performance along with occupant comfort. Moreover, in this figure,  $UDI_{100-2000lux}$  percentage is displayed at the height of 0.8 m above the floor, before and after optimization. The warmer colors represent a higher level of received daylight. It can be indicated that the 2nd, 3rd, 8th, and 9th solutions have the highest  $UDI$  value on both the tables and blackboard, among others.

In Figs. 11 and 12, the values of  $ASE$  and  $DGP$  are measured for the reference class and the selected optimal solutions. These measurements prove that the 2nd, 3rd, 8th, and 9th solutions with the highest amount of  $UDI$  also have the highest level of  $DGP$  and  $ASE$  throughout the year. Nonetheless, as it is shown in annual  $DGP$  charts, for none of the optimum solutions, the maximum value of  $DGP$  among all the hours of a whole year has exceeded the limit of 0.35. This implies that visual comfort conditions are fulfilled without any need for additional tools for controlling the amount of daylight entering the room.

**Table 8**  
Comparison of annual daylight performance metrics.

Classroom designs	UDI <sub>100–2000</sub> (tables) (%)	UDI <sub>100–2000</sub> (board) (%)	UDI <sub>100–2000</sub> (total) (%)	DA (total) (%)	ASE (%)	DGP
Base case	66.88	71.31	67.36	44.28	0	0.23035
1st solution	23.03	16	22.62	7.22	0	0.19873
2nd solution	38.86	51.38	40.73	16.05	4	0.21651
3rd solution	43.09	52.36	44.02	20.45	10	0.22747
4th solution	14.69	4.20	13.16	4.05	1	0.19383
5th solution	19.64	11.79	18.90	4.28	0	0.20759
6th solution	11.41	5.92	10.24	1.16	0	0.13335
7th solution	11.22	2.87	10.30	2.33	0	0.18118
8th solution	54.67	62.41	56.10	25.94	14	0.23113
9th solution	48.64	60.08	50	24.56	14	0.22901
10th solution	19.04	12.15	17.47	4.75	0	0.16423

**Table 9**  
Comparison of inputs and outputs for two selected options.

	Inputs				Outputs				
	Wall inclination angle	WWR (%)	Orientation	Window. Number	UDI (%)	DA (%)	TEUI(kWh/m <sup>2</sup> )	LEUI(kWh/m <sup>2</sup> )	CTR (%)
1st option	10°	60	0°	3	58.07	55.51	113.19	35.30	78.37
2nd option	10°	60	0°	5	57.91	55.38	113.21	35.31	78.38

**Table 10**  
Impacts of wall inclination angle on design objectives.

Wall inclination angle	UDI (%)	DA (%)	ASE (%)	TEUI (kWh/m <sup>2</sup> )	LEUI (kWh/m <sup>2</sup> )	CTR (%)
−30°	59.91	57.35	14	140.01	22.96	84.07
−20°	63.16	52.10	9	127.80	22.99	84.78
−10°	65.66	48.07	2	125.82	23.03	85.00
0° (base case)	67.36	44.28	0	125.84	23.07	85.16
+10°	68.29	39.78	0	126.56	23.11	85.03
+20°	67.40	34.17	0	130.56	23.20	85.09
+30°	64.96	27.40	0	133.97	23.27	84.86

**Table 11**  
Impacts of WWR on design objectives.

WWR (%)	UDI (%)	DA (%)	ASE (%)	TEUI (kWh/m <sup>2</sup> )	LEUI (kWh/m <sup>2</sup> )	CTR (%)
20%	11.74	0.63	0	103.47	31.53	85.88
30%	31.60	7.56	0	107.06	24.83	85.79
40%	50.71	18.54	0	112.00	23.52	85.65
50%	64.46	31.95	0	118.28	23.22	85.48
60% (base case)	67.36	44.28	0	125.84	23.07	85.16
70%	65.67	55.24	1	134.54	22.99	84.39
80%	62.31	63.48	5	144.43	22.94	83.66

## 5. Validation

Over the past years, validation of Honeybee and Ladybug plug-ins have successfully accomplished by several papers. Therefore, in this research, these plug-ins were utilized in daylight and energy simulation (Elwy et al., 2018; Donato et al., 2017; Aksamija, 2011).

To test the validation of carried out simulation, the first step was to select two close solutions on the Pareto front, and their objective functions were calculated and compared with each other. Since the input variables in both cases are similar to one another except for the number of windows, the results are expected to be slightly different. In Table 9, the obtained values for these two solutions are represented.

Also, the values of the objective functions for 4 randomly chosen solutions in the Pareto chart are assessed in Fig. 13. The comparison of these numbers proves that the results are logically correct.

Single clear is utilized as glazing material in Fig. 13 and Table 9.

### 5.1. Sensitivity analysis

In order to carefully examine the relations between the parameters and design objectives, the amount of every variable has been modified individually for the base case, with all the other variables being unchanged. Tables 10–13, and 14 illustrate the results of these analyses.

The glazing material in Tables 10–12, and 13 is considered as single clear. Also, the base case is assumed to be divided into multiple, independently controllable lighting zones.

It can be observed that among all the design variables, WWR is highly influential on thermal demand, daylight metrics (UDI

**Table 12**  
Impacts of building orientation on design objectives.

Building orientation	UDI (%)	DA (%)	ASE (%)	TEUI (kWh/m <sup>2</sup> )	LEUI (kWh/m <sup>2</sup> )	CTR (%)
0°	55.44	58.57	41	116.30	23.02	77.43
45°	57.02	53.68	54	130.00	23.11	80.92
90°	61.06	48.17	58	140.30	23.14	83.22
135°	65.01	43.21	19	139.29	23.13	84.50
180° (base case)	67.36	44.28	0	125.84	23.07	85.16
225°	65.47	52.07	19	135.05	22.95	84.65
270°	60.74	59.60	59	137.42	22.91	82.13
315°	57.27	61.47	51	129.70	22.92	78.57

**Table 13**  
Impacts of number of windows on design objectives.

Number of windows	UDI (%)	DA (%)	ASE (%)	TEUI (kWh/m <sup>2</sup> )	LEUI (kWh/m <sup>2</sup> )	CTR (%)
1	65.37	43.39	0	150.46	22.89	83.27
2	67.18	44.42	0	125.84	23.08	85.16
3 (base case)	67.36	44.28	0	125.84	23.07	85.16
4	67.31	43.78	0	125.84	23.07	85.16
5	67.21	43.42	0	125.84	23.07	85.16
6	67.56	43.54	0	125.84	23.07	85.17
7	67.59	43.75	0	125.84	23.07	85.17

**Table 14**  
Impacts of glazing material on design objectives.

Glazing material index	UDI (%)	DA (%)	ASE (%)	TEUI (kWh/m <sup>2</sup> )	LEUI (kWh/m <sup>2</sup> )	CTR (%)
0	67.36	44.28	0	112.71	23.18	86.07
1	67.36	44.28	0	116.9	23.13	85.89
2 (base case)	67.36	44.28	0	125.84	23.07	85.16



and *DA*), and electric lighting energy. Building orientation has the most effect on *ASE* and occupant thermal comfort. Number of windows is the least influential input variable. Also, as expected, the wall inclination angle plays a determining role in the value of *DA*.

## 6. Conclusion

The presented framework in this article enables architects to access an efficient methodology for achieving a set of best design options for a classroom from the Pareto front, with the assistance of parametric design, and then make their final decision based on their individual preferences by comparing the visual comfort of optimum solutions. Therefore, there is not any finalized and determined design solution. However, the results of this survey can be a useful guidance for architects to select the best possible solution with regard to the specific school design objectives and requirements, which can vary from one project to another. Overall, the outcome of utilizing this method in initial stages of design is a sustainable building that provides the highest level of thermal comfort for its user in exchange for the lowest amount of energy consumption or, in other words, the least environmental harm.

The results of this study prove that:

- Among design options with identical conditions (building orientation, *WWR*, glazing material and the angle between the wall containing windows and vertical direction) and different number of windows, the ones with more windows have less *DA* and *DGP* values.
- Consideration of multiple zones for the purpose of controlling the amount of illuminance in each zone based on the proper level of light needed for the task that is performed in every zone, not only improves occupants' visual comfort but also reduces lighting energy consumption up to 48%.
- Using a triple glazed window compared with double glazed and single glazed window results in the reduction of consumed energy, increase of thermal comfort, and a slight growth in electric lighting energy demand.
- Compared with other design variables, *WWR* can have a considerable impact on cooling and heating energy, daylight metrics (*UDI* and *DA*), and electric lighting energy while building orientation highly influences *ASE* and occupant thermal comfort. Additionally, the wall inclination angle plays a vital role in determining *DA* levels.

In conclusion, using a strategy similar to the one that was applied in this paper, in the design process of any building is significantly helpful for designers, inhabitants and the environment; in the way that it saves time and money, guarantees the supply of users' comfort and contributes to the preservation of the environment.

In future works, minimization of discomfort glare with the use of various shading systems and comparison of them to find the most suitable system can be implemented as the second phase of optimization. Examination of this objective was not possible in this research since the calculation concerning each of the analyses of *DGP* and shading systems is compute-intensive. Consequently, considering both of these calculations simultaneously, was very time-consuming. Furthermore, architects need to notice that acoustic comfort is one of the critical aspects of users' comfort, and it should be considered in the design procedure. Hence, more researches are required in the field of facilitating the evaluation of acoustic comfort for indoor environments, especially educational spaces, with the use of visualizable computer programs.

## CRediT authorship contribution statement

**Parnian Bakmohammadi:** Visualization, Validation, Resources, Investigation, Data curation, Formal analysis, Writing - original draft, Software, Writing - review & editing. **Esmatullah Noorzai:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Resources, Writing - original draft, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

- Abbasi, O., Noorzai, E., Gharouni Jafari, K., Golabchi, M., 2020. Exploring the causes of delays in construction industry using a cause-and-effect diagram: a case study for Iran. *J. Arch. Eng.* [http://dx.doi.org/10.1061/\(ASCE\)AE.1943-5568.0000431](http://dx.doi.org/10.1061/(ASCE)AE.1943-5568.0000431).
- Aksamija, A., 2011. Methods for integrating parametric design with building performance analysis. <<https://www.arcc-journal.org/index.php/repository/article/view/459/363>>.
- Alhagla, K., Mansour, A., Elbassuoni, R., 2019. Optimizing windows for enhancing daylighting performance and energy saving. *Alexandria Eng. J.* 58 (1), 283–290.
- ASHRAE, 2005. *ASHRAE Handbook: Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta.
- ASHRAE, 2010. *ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta.
- ASHRAE, 2013. *ANSI/ASHRAE Standard 169-2013: Climatic Data for Building Design Standards*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta.
- Carlucci, S., Causone, F., De Rosa, F., Pagliano, L., 2015. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. *Renew. Sustain. Energy Rev.* 47 (C), 1016–1033.
- Chłodowicz, E., Orlowski, P., 2016. Comparison of a Perpetual and PD inventory control system with smith predictor and different shipping delays using bicriterial optimization and SPEA2. *Kwart. Pomiar. Autom. Robot.* 1, 5–12.
- de Bruin-Hordijk, T., de Groot, E., 2007. Energy efficient Lighting in Classrooms. In: *IEA ECBCS Annex 45 Newsletters*. pp. 1–5, <[http://www.lightinglab.fi/IEAAnnex45/guidebook/guidebook\\_summary\\_report.pdf](http://www.lightinglab.fi/IEAAnnex45/guidebook/guidebook_summary_report.pdf)>.
- de Dear, R.J., Brager, G., 1998. Developing an adaptive model of thermal comfort and preference. *ASHRAE Trans.* 104, 145–167.
- de Dear, R.J., Brager, G., 2002. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy Build.* 34 (6), 549–561.
- de Dear, R., Schiller Brager, G., 2001. The adaptive model of thermal comfort and energy conservation in the built environment. *Int. J. Biometeorol.* 45, 100–108.
- Donato, M., Zemella, G., Rapone, G., Hussain, J., Black, C., 2017. An innovative app for a parametric, holistic and multidisciplinary approach to early design stages. *J. Façade Des. Eng.* 5 (2), 113–127.
- Eltawee, A., Su, Y., 2017. Parametric design and daylighting: A literature review. *Renew. Sustain. Energy Rev.* 73, 1086–1103.
- Elwy, I., Ibrahim, Y., Fahmy, M., Mahdy, M., 2018. Outdoor microclimatic validation for hybrid simulation workflow in hot arid climates against ENVI-met and field measurements. *Energy Procedia* 153, 29–34.
- Futrell, B.J., Ozelkan, E.C., Brentrup, D., 2015a. Bi-objective optimization of building enclosure design for thermal and lighting performance. *Build. Environ.* 92, 591–602.
- Futrell, B.J., Ozelkan, E.C., Brentrup, D., 2015b. Optimizing complex building design for annual daylighting performance and evaluation of Optimization algorithms. *Energy Build.* 92, 234–245.
- Gharouni Jafari, K., Ghazi Sharyatpanahi, N.S., Noorzai, E., 2020. BIM-based integrated solution for analysis and management of mismatches during construction. *J. Eng. Design Tech.* <http://dx.doi.org/10.1108/JEDT-02-2020-0044>.
- Gharouni Jafari, K., Noorzai, E., Makkiabadi, S.R., HeshmatNezhad, R., 2014. Providing a model to select a proper delivery system for railway projects in Iran. *ISAHp 2014 Conference - Washington DC*. <http://dx.doi.org/10.13033/isahp.2014.140>.
- Golabchi, M., Noorzai, E., Golabchi, A., Gharouni Jafari, K., 2016. *Building Information Modeling*. Tehran University Press.



- Hafiz, D., 2015. Daylighting, space, and architecture: a literature review. *A J. Archit. Res.* 12 (1), 2329–9339.
- IESNA, 2012. LM-83-12 IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). IESNA Lighting Measurement, New York, USA.
- Jabi, W., 2013. Parametric Design for Architecture. Laurence King, London, UK.
- Konis, K., Gamas, A., Kensek, K., 2016. Passive performance and building form: An optimization framework for early-stage design support. *Sol. Energy* 125, 161–179.
- Lagios, K., Niemasz, J., Reinhart, C.F., 2010. Animated building performance simulation (abps) – linking rhinoceros/grasshopper with radiance/daysim.
- Lee, K.S., Han, K.J., Lee, J.W., 2017. 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 (5), 635–655.
- Mahdavinnejad, M., Mohammadi, S., 2016. Parametric optimization of daylight and thermal performance through louvers in hot and dry climate of Tehran. *J. Fundam. Appl. Sci.* 8 (3), 1221–1236.
- Mangkuto, R.A., Dewi, D.K., Herwandani, A.A., Koerniawan, M.D., Faridah, 2019. Design optimisation of internal shading device in multiple scenarios: Case study in Bandung, Indonesia. *J. Build. Eng.* 24, 100745.
- Moreno, M.B.P., Labarca, C.Y., 2015. Methodology for assessing daylighting design strategies in classroom with a climate-based method. *Sustainability* 7 (1), 880–897.
- Nabil, A., Mardaljevic, J., 2005. Useful daylight illuminance: a new paradigm for assessing daylight in buildings. *Light. Res. Technol.* 37 (1), 41–57.
- Nicol, J.F., Roaf, S., 2017. Rethinking thermal comfort. *Build. Res. Inf.* 45 (7), 711–716.
- Nicol, F., Stevenson, F., 2013. Adaptive comfort in an unpredictable world. *Build. Res. Inf.* 41 (3), 255–258.
- Noorzai, E., 2020. Performance analysis of alternative contracting methods for highway construction projects: A case study for Iran. *J. Infrastruct. Syst.* [http://dx.doi.org/10.1061/\(ASCE\)IS.1943-555X.0000528](http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000528).
- Noorzai, E., Golabchi, M., 2020. Selecting a proper construction system in small and medium mass housing projects, considering success criteria and construction volume and height. *J. Eng. Des. Tech.* <http://dx.doi.org/10.1108/JEDT-09-2019-0227>.
- Pilechiha, P., Mahdavinnejad, M., Pour Rahimian, F., Carnemolla, P., Seyedzadeh, S., 2020. Multi-objective optimisation framework for designing office windows: quality of view, daylight and energy efficiency. *J. Appl. Energy* <http://dx.doi.org/10.1016/j.apenergy.2019.114356>.
- Qingsong, M., Fukuda, H., 2016. Parametric office building for daylight and energy analysis in the early design stages. *Procedia - Soc. Behav. Sci.* 216, 818–828.
- Rea, M.S., 2000. *The IESNA Lighting Handbook Illuminating Engineering*. Society of North America, New York, NY, USA.
- Reinhart, C.F., Walkenhorst, O., 2001. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy Build.* 33 (7), 683–697.
- Serghides, D., Dimitriou, S., Kyprianou, I., Papanicolas, C., 2017. The adaptive comfort factor in evaluating the energy performance of office buildings in the mediterranean coastal cities. *Energy Procedia* 134, 683–691. <http://dx.doi.org/10.1016/j.egypro.2017.09.588>.
- Shahbazi, Y., Heidari, M., Haghparast, F., 2019. An early-stage design optimization for office buildings' facade providing high-energy performance and daylight. *Indoor Built Environ.* 28 (10), 1350–1367.
- Shove, E., 2003. Converging conventions of comfort, cleanliness and convenience. *J. Consum. Policy* 26 (4), 395–418.
- Sun, C., Han, Y., Feng, H., 2015. Multi-objective building form optimization method based on GANN-BIM model. *Next Gener. Build.* 2 (1), 141–154.
- Tabadkani, A., Banihashemi, S., Hosseini, M.R., 2018. Daylighting and visual comfort of oriental sun responsive skins: A parametric analysis. *Build. Simul.* 11 (4), 663–676.
- Tabadkani, A., Shoubi, M.V., Soflaei, F., Banihashemi, S., 2019. Integrated parametric design of adaptive facades for user's visual comfort. *Auto. Const.* 106, 102857.
- Taghizade, K., Heidari, A., Noorzai, E., 2019. Environmental impact profiles for Glazing systems: Strategies for early design process. *J. Archit. Eng.* 25 (2), [http://dx.doi.org/10.1061/\(ASCE\)AE.1943-5568.0000343](http://dx.doi.org/10.1061/(ASCE)AE.1943-5568.0000343).
- Tahsildoost, M., Zomorodian, Z.S., 2015. Energy retrofit techniques: An experimental study of two typical school buildings in Tehran. *Energy Build.* 104, 65–72.
- Touloupaki, E., Theodosiou, T., 2017. Optimization of building form to minimize energy consumption through parametric modelling. *Procedia Environ. Sci.* 38, 509–514.
- Trachte, S., De Herde, A., 2015. Sustainable Refurbishment School Building Int. Energy Agency, Leuven, <[www.iea-shc.org/data/sites/1/publications/subt.D.SchoolRenovation.022015.pdf](http://www.iea-shc.org/data/sites/1/publications/subt.D.SchoolRenovation.022015.pdf)>.
- Wang, R., Lu, S., Feng, W., 2020a. Impact of adjustment strategies on building design process in different climates oriented by multiple performance. *J. Appl. Energy* <http://dx.doi.org/10.1016/j.apenergy.2020.114822>.
- Wang, R., Lu, S., Feng, W., 2020b. Impact of adjustment strategies on building design process in different climates oriented by multiple performance. *J. Energy* <http://dx.doi.org/10.1016/j.energy.2019.116723>.
- Wienold, J., Christofferson, J., 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy Build.* 38 (7), 743–757.
- Zahiri, S., Sharples, S., Altan, H., 2011. Developing Sustainable School Design in Iran: A thermal comfort survey of a secondary school in Tehran. *Plea* 2011 1, 523–528.
- Zhang, A., Bokel, R., Dobbeltstein, A.V.D., Sun, Y., Huang, Q., Zhang, Q., 2017. Optimization of thermal and daylight performance of school buildings based on a multi-objective genetic algorithm in the cold climate of China. *Energy Build.* 139, 371–384.
- Zomorodian, Z.S., Nasrollahi, F., 2013. Architectural design optimization of school buildings for reduction of energy demand in hot and dry climates of Iran. *Int. J. Archit. Urban Plann.* 23 (1), 41–50.