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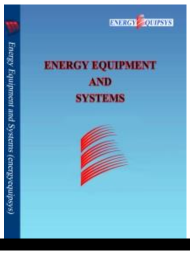

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The effect of using smart shadings on the thermal and visual performances of buildings in Iran: A numerical simulation

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ABSTRACT

This paper presents controlling and optimizing the energy performance of buildings using smart shadings. Simulations are carried out using EnergyPlus and multi-objective optimization is performed by jEPlus+EA through NSGA-II algorithm. Optimization of control strategies is performed for a typical office room on the middle floor of a building in Tehran. Slat angle, solar radiation, and the material of smart windows are selected as decision variables. Also, the annual total building energy consumption, the predicted percentage of dissatisfaction (PPD), and the discomfort glare index (DGI) are considered as three objective functions minimized simultaneously. The weighted sum method to select the final answer of Pareto solutions is used. In the first strategy, a comparison of the results of optimization with the initial values when the angles of slats are constant and equal to 45 ° showed that the total annual energy consumption, DGI, and PPD indexes reduced up to 11.74%, 6.4%, and 46.6%, respectively. In the second strategy, the reductions were 28.73, 56.50, and 34.05%, respectively, in comparison with the double-glazing window. The results clearly show how the correct selection of architectural parameters and control strategies can greatly prevent energy losses while providing the thermal and visual comfort of the building occupants.

Keywords: Shading Control Strategy; Multi-Objective Optimization; Thermal Comfort; Visual Comfort; Building Energy Simulation.

1. Introduction

Energy is one of the most essential factors for the development of the country. Human needs continuous energy sources. It has been a fundamental issue in human life. With the growth of industry and limited fossil resources, human beings have moved towards the optimal use of energy. The buildings in each country have a high scarcity in energy consumption, which due to high energy losses in the country's buildings and rising prices of energy carriers in recent years, has paid special attention to energy management in buildings, including the construction of smart buildings [1]. It is important to note that about 40% of the total annual energy consumption and 36% of the total carbon dioxide emissions are related to

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buildings, which has a significant share [2]. Buildings have a wide role in storing and saving energy, more than other consumers [3, 4].

Windows plays a key role in building energy performance. They are the only source of direct solar energy entering the building, providing heat and light at the same time, and may cause overheating [5]. Hence, choosing an appropriate automatic control strategy on the slat angle can have a great influence on the building's performance. Another way to reduce energy consumption, as well as control and limit the light entering the building for the thermal and visual comfort of residents, is to use smart glazing windows, the material of which changes according to certain environmental conditions. Many research works have been done on control strategies for the use of shadings using the control capability of EnergyPlus software called Ems, as well as energy optimization in buildings by smart glazing windows. Tebadkani et al. [6] Inspired by origami design and using Honeybee software, EMS EnergyPlus, and Ladybug have designed a smart hexagonal shading, which the user can adjust the amount of light entering the room at any time without any restrictions based on their needs. Wang et al. [7] researched to investigate the effects of windows on building performance for different types of ventilation systems, including convection ventilation and conventional VAV systems in an office building. For each system, EnergyPlus simulation software is used, in which the EMS section is used to control the air conditioning based on the thermal comfort index and energy consumption. Firlag et al. [8] research on moving window control algorithms for they did residential buildings. They used and compared five different algorithms and used EnergyPlus software to model one engine and four sensors to implement control algorithms on the window. They also used WINDOW software for window specifications. They used EMS of EnergyPlus software for control algorithms and obtained results for four different climatic zones. In this study, they found that using automatic shading can reduce energy consumption by 11 to 13 percent. They also found that control algorithms had a strong effect on the performance of shadings. Yeon et al. [9] performed research on an artificial intelligence technique in automatic blind slat angle control in which an artificial neural network model minimizes the total energy consumption of a building, including cooling, heating, and lighting energy. A three-story office building simulated by EnergyPlus software that uses Dimming to control it. Communication between MATLAB software and EnergyPlus through BCVTB. As a result of their work, the automatic control of the blind slat angle consumed 9.1% less than the 50° slat angle fixed mode. Kirimtat et al. [10] reviewed the modeling and simulation of shading in a building. According to them, by making architectural changes in the building, it is possible to minimize energy consumption. In the design of these buildings, in the early stages of design, attention should be paid to the shading components. This is especially important in places with hot summers. It is very important to protect the window from the sun in summer while allowing the maximum amount to enter in the summer. Yun et al. [11] discussed the importance of external blind control and its effect on energy consumption and the comfort of residents. The purpose of their research is to provide a method for calculating the appropriate threshold for activating the blinds and the slat angle of the external blinds in different conditions. The variables they use are weather conditions, building direction, window-to-wall ratio, and control target (weight coefficient). The performance of blinds is evaluated based on the discomfort glare index (DGI) and light energy consumption. They concluded that the blinds should have a larger slat angle so that occupants could reach more comfort, and conversely, if the energy parameter was taken into account, performance would be better if the blinds were not used. Hoffmann et al. [12] balanced the three goals of energy, glare, and daylight using transparent wall simulation tools and shading systems. In this study, they investigated 12 different shade models in different geographies, materials, and cut-off angles in two different weather conditions in California. They used EnergyPlus, WINDOW, and Radiance software to calculate the heat transfer, glare, and brightness. They examined two different systems, one with constant lighting energy consumption and the other by examining the daylighting control system. An optimal blind slat angle has been identified for each case. They showed that material properties for the use of the energy consumption of the first system do not affect, which constant electrical lighting was assumed, but have a significant effect on the second one. Xiong et al. [13] used dynamic facades with lighting and shading control to affect visual comfort and reduce lighting energy consumption. They used two different sensors in the building facade to control the glare and used three different indicators of daylight glare probability (DGP), daylight brightness, and vertical illumination as target functions. They improved the shading operation and, at the same time, reduced the discomfort of occupants and increased the life of the equipment. Bellia et al. [14] provide an overview of the shading systems in buildings. In recent years, various types of shades have been investigated, depending on the orientation and location of the building, characteristics of windows, and so on. They will be able to improve or weaken the thermal and lighting performance of the building from both the energy and comfort perspectives of the residents. In their article, they report on the critical analysis of some studies that examine the impact of shading devices on building energy and lighting performance and found that it is difficult to compare tasks due to different weather conditions, locations, specifications, and methods. So, protocols are needed to make the work done globally comparable. Also, according to their observations, very little research has been done on the effect of the presence of shading devices on thermal comfort, and economic and environmental issues. Konstantoglou et al. [15] reviewed studies on shading systems and lighting performance control. According to their research, unlike static systems, the use of automatic shades and automatic lighting systems are increasingly being used in building facade design to improve their energy performance. The most important question that arises is which of these systems has the best impact on building energy performance and the thermal and visual comfort of the residents. They examined a motorized blind and observed the effect of different strategies on it, and found that according to the findings of the articles, energy-saving with automatic blind control depends on the type of control strategy and its relationship with the dimmable electrical lighting system. Scarning et al. [5] investigated the effect of dynamic solar shading on the overheating of residential buildings with insulated walls. Their research examines the effect of the combination of different glazing specifications, window dimensions, and different dynamic shading scenarios on the energy consumption, daylight, and thermal comfort of a low-heating load building. During this study, they found that in special conditions with the presence of dynamic shading, thermal comfort up to 15% improvement. Oleskowicz et al. [16] investigated the effect of roller blinds on heat loss through double-glazed and low-emissivity glasses, in the hot season nights in Central Europe. Parameters hourly air temperature, wind speed, and temperature of the sky. They showed that the use of internal and external roller shutters, approximately 33% and 45% reduce window heat loss. They also did the same for windows with the emissivity of less than and achieved similar results. Tzempelikos et al. [17] investigated the effect of design and control of shading on the energy required for cooling and lighting of the building. In their research, the simultaneous effect of window area, shading characteristics, and its control on the energy requirement of cooling and lighting has been calculated using the simulation method of thermal and lighting coupled the interaction between lighting energy consumption and cooling in the environment is evaluated by a function of the window to wall ratio and shading parameters. In their research, they used external roller blinds. They concluded that if a comprehensive approach to motorized shading with a lighting power control system was considered, a significant reduction in energy consumption would be achieved. Debra, Dubrow, and Krarti [18] were able to find a new way to design residential buildings by researching building energy optimization methods. To implement their method, they coupled the genetic algorithm to a building energy simulation engine called DOE-2 software. Then, by performing an optimization-based simulation process, a set of different building shapes including rectangular, L-shaped, T-shaped, and trapezoidal, as well as other parameters related to the building form, including wall and roof structures, types of insulation, types of windows, and their surfaces.

They considered minimizing the energy consumption of residential buildings. The results of their optimization showed that the rectangular and trapezoidal structure always has the best performance (lowest life cycle cost) in five different climates. Shan [19] studied the optimization of the facade characteristics of an office building by considering decision-making design variables such as the size of the shading protrusion and the dimensions of the window. He chose his target functions as the total energy consumption of lighting, heating, and cooling to achieve the lowest annual energy cost. Then, to model the energy consumption of the building, he used the TRNSYS simulation program to find the optimal design parameters of the genetic algorithm. The results of his research were that the use of a simulation-based optimization method and the use of the genetic algorithm, in addition to sufficient accuracy in the optimal point answer, the optimization process takes place in the shortest possible time and allows building engineers and architects to perform optimal design with the least error and the fastest possible time. Delgarm et al. [20] offered an efficient approach to simulation-based multi-objective optimization problems that demonstrate important constraints on building energy performance. In their study, single and multi-objective optimization algorithms with building energy simulation software, EnergyPlus have been associated. Decision variables in their research included window dimensions, overhang depth, wall material, and so on. They optimized the total energy consumption of the room, including cooling, heating, and cooling energy in four different climates of Iran. Naderi [21] proposed a multi-objective simulation based on the architectural specifications and control parameters of a smart shading blind. Using the proposed method, the implementation of control strategies on the window shading device and simultaneous optimization leads to a significant reduction in building energy consumption and occupants' thermal and visual discomfort. Simulations are performed using EnergyPlus, objective functions, and decision parameters are specified by jEPlus, and multi-objective optimization is performed by jEPlus+EA via NSGA-II. Controlled blind optimization is performed in a typical office room located on the middle floor of a building, and the results are evaluated for four window orientations in six different climatic regions of Iran according to the Köppen-Geiger climate classification. Decision variables are shading control strategy and its set points and dimensions, angle, material, and shading location. Total annual energy consumption of the building, PPD, and DGI are also considered as three objective functions minimized simultaneously. The weighted sum method to select the final answer of Pareto solutions is used. Based on the results, based on the weather and window orientation, the proposed optimization method leads to a reduction of 2.8-47.8 in total annual energy consumption of the building compared to the original design simultaneously with 15.5-69.9, and 8.5-56.3% in DGI and PPD indexes, respectively. The results clearly show how the proper choice of shading specifications and their control strategy can not only significantly prevent energy loss but also provide better occupants' thermal and visual comfort. More recently, Krarti [22] evaluated the effect of using a rotating overhang system for office buildings in warm climates. They reported that the proposed system has an energy-saving potential of up to around 40% which is most similar to the energy use intensity reduction reported by De Luca et al. [23]. In another research work, Valitabar et al. [24] optimized a multi-layer blind system through a brute-force algorithm to control the glare in an office room.

In this research, a smart shading system is presented and optimized to minimize the building's annual energy consumption while simultaneously increasing the thermal and visual comfort of the occupants. To achieve these goals, simulations are performed using EnergyPlus, and the shading controlling algorithm is optimized by jEPlus+EA through the NSGA-II algorithm. The main contributions and novelties of the current study are:

- Proposing a smart shading system with controllable blades slat angle;
- Optimizing the shading control strategy to reduce the building energy consumption while enhancing the occupants' comfort indexes;
- Evaluating the effect of using smart thermochromic glazing on the building performance in climatic conditions of Iran.

2. Methodology

2.1 Building Energy Simulation Software

Due to energy and its excessive consumption in the construction sector, analysis and study of energy consumption in this sector have a great place. Therefore, for energy analysis, building energy simulation software is used. Building simulation software is a computer program used to simulate the hourly energy consumption of buildings. Due to the complex design of modern buildings, as well as the optimal development of building modeling and analysis software, their use has become very popular today. One of the oldest and most inaccurate energy analysis software for calculating the thermal load of a building is Carrier-Hap software, which in most developed countries, the use of this software is obsolete. Over time, up-to-date building energy analysis software increased the accuracy and speed of their analysis, and more powerful and accurate software such as DOE-2 and TRNSYS has been introduced, which became very popular among architects and engineers. EnergyPlus software is designed based on a combination of the best features of DOE-2 and Blast programs. EnergyPlus is an energy analysis and thermal simulation software that according to the description of the building based on the physical structure, systems, and features entered by the user, provides various outputs such as heating and cooling needs, temperature of thermal zones, wall temperatures, and many other outputs. Although EnergyPlus has many capabilities, it cannot perform any optimization operation. Therefore, secondary software is needed for this purpose. This study uses jEPlus+EA as an optimization program. The software was developed in the Java programming language and was first published by Yi Zhang at the Institute of Energy and Sustainable Development, the University of Montfort in 2009. jEPlus is also used to define EnergyPlus design parameters as decision variables and EnergyPlus outputs as objective functions. jEPlus enables users to perform a parametric study of arbitrary input parameters through EnergyPlus and TRNSYS [25, 26].

2.2 Energy Management System (EMS)

The Energy Management System (EMS) is one of the high-level control methods available in EnergyPlus that can be used to control many things. Including the construction of energy-related systems such as heating, cooling, and ventilation as well as indoor and outdoor lighting, mechanized systems to control shadings, and moving windows [27]. This part of EnergyPlus software can access a wide range of sensor data and uses this data to guide a variety of control algorithms. The programming language of this part is called EnergyPlus Erl1 software, which is used to encode control algorithms. The EMS itself consists of three main parts, which are the EMS Sensor, the EMS Actuators, and the EMS Calling Points. In the first part, the necessary sensors to control the desired inputs are defined. In the second part, one or more actuators are entered according to the need for defined sensors. In the last part, programs are written to activate all sensors.

2.3 Visual Comfort Index

EnergyPlus software uses the Discomfort Glare Index (DGI) to calculate visual comfort. The user must give a reference point to the software to calculate the index accordingly. For office buildings, the maximum allowable limit of this index is 22, which should be considered in the calculations. Table 1 shows this amount for different places [28].

Table 1. Maximum allowable DGI allowed in different places [28].

Activity or Zone Type	Maximum Allowable DGI
Art Galleries	16
Factories: Rough work	28
Factories: Engine assembly	26
Factories: Fine assembly	24
Factories: Instrument assembly	22
Hospital wards	18
Laboratories	22
Museums	20
Offices	22
School classrooms	20

Discomfort Glare causes a person to instinctively turn his eyes off a light source or to find it difficult to see [29]. DGI is the most widely cited model for predicting unpleasant flexibility [30] and is defined as [31]:

$$DGI = 10\log_{10}\left[0.478\sum_{i=1}^{n}\left(\frac{L_{si}^{1.6}\Omega_{si}^{0.8}}{L_b + 0.07\,\Omega_{si}^{0.5}L_{win}\,P_i^{1.6}}\right)\right] \quad (1)$$

L_{si}, L_{sb}, and L_{win} is the luminance of the glare source, the background, and the window in “cd/m2”, respectively. Ω_{si} is the solid angle that is adjusted by the glare source from the occupants' point of view and corrected by the Goths’ position indicator, i.e., P_i . n is the number of glare sources [31].

2.4 Thermal Comfort Index

Providing thermal comfort to people in man-made spaces is one of the main goals of architectural design because it is in such conditions that people living in space can work with maximum efficiency and mental and physical ability in the best way. Thermal comfort is the state in which a person does not take any behavioral action to change the ambient temperature conditions. In the definition of the ASHRAE 55 standard, thermal comfort is a sensory condition that expresses a sense of satisfaction with the ambient temperature conditions. Maintaining this standard of thermal comfort for building occupants is one of the important goals of engineers. The main factors that affect comfort are those that play a role in heat dissipation and absorption, including clothing insulation, ambient temperature, mean radiant temperature, air velocity, and relative humidity (RH) [32]. The Fanger’s Predicted Mean Vote (PMV) estimation model is the best among the known comfort models. This model is obtained using the principles of thermal equilibrium and experimental data obtained from rooms under constant weather conditions. The Standard Thermal Comfort Questionnaire assesses samples for their sense of temperature on a seven-point scale from very cold (-3) to very hot (+3). Zero is the ideal value for it, indicating that the sensation of heat or cold is neutral. The comfort zone is defined by a combination of six parameters in which PMV in the proposed range, ranges from -0.5 to +0.5 [33]. PPD should be below 10% [34, 35]. The following equation shows the relationship between PMV and PPD:

$$PPD = 100 - 95exp\left(-0.03353PMV^4 - 0.2179PMV^2\right) \quad (2)$$

2.5 Control Strategies

One of the goals of this research is to implement a series of control strategies for the windows, which include the control strategy of changing the blind slat angle and the control strategy of the smart window. This paper aims to create a control strategy on the slat angle of the blades, which according to the need, changes the blades slat angle and provides thermal and visual comfort to the residents by controlling the amount of sunlight entering the building. This control scheme itself contains many parameters that can be used as decision-making variables and optimize the defined objective functions. These control strategies are defined as a coding program in the software. Then, using coding, objective functions and selected decision-maker parameters of the simulator software were specified to the optimizer software, jEPlus+EA, and the optimization operation was performed by the NSGA-II algorithm.

2.5.1 Shading slat angle control strategy

To write a program coded in this strategy, energy modeling was first taken from the modeled building with the inner blind shading for both windows with the shading blade slat angle so that it is fixed and equal to 45°, and the output of the solar radiation is taken. According to the way it changes in the hot and cold seasons of the year, a control program was written by EMS EnergyPlus capability. In the EMS section of the software, several 66 sensors are defined to measure the amount of sunlight, and indoor and outdoor air temperature, as well as sensors of the heating and cooling system, each of which needs its activators to activate. In the software program section, it is done in such a way that it can be divided into two parts:

- When the temperature inside the room is lower than the outside temperature and the cooling system is on, the shading slat angle is at zero degrees to each other, and if the heating system is on, they will be at 90° to each other. If both systems are off, the slat angle is zero degrees.

- If the temperature inside the room is higher than the temperature outside, according to Table 2, three states are created.

In the optimization part of this strategy, the range of changes in slat angle and also the range of changes in incident solar radiation using jEPlus+EA software are discussed.

2.5.2 Smart window control strategy

The control program is written by the EMS EnergyPlus feature. In the EMS section, a sensor for measuring outside room temperature is defined separately for both windows, which need their activators to activate each. In the software program, it has been done in such a way that it can be described that the glass material of each window is assumed to be thermochromic, with this control program, 19 types of thermochromic windows are considered for each window. It is assumed that each is related to a specific temperature range that will change according to the temperature sensor outside the room at what temperature range. In the optimization part of this strategy, the type of thermochromic window is optimized using jEPlus+EA software.

2.6 Multi-objective Optimization

In multi-objective optimization issues, we are dealing with different criteria that are widely used today in various fields such as economics, engineering, etc. Objective functions in multi-objective optimization problems usually move in opposite directions, so that by increasing one function, we see a decrease in the function or other functions. A set of solutions that do not lead from each other is called the Pareto front [36, 37]. The most famous multi-objective optimization algorithms in the field of Non-Dominated Sorting Genetic Algorithm (NSGA) [38]. The second version was introduced as NSGA-II in 2002 [26]. Multi-objective simulation based on building energy optimization has been performed using jEPlus+EA software in this research [26]. In this way, the decision-making design parameters in EnergyPlus are classified by jEPlus software, and the range of permissible changes for each is defined. Also, with a code in rvx format, all the target functions are defined according to the outputs of the EnergyPlus software for jEPlus, so that they can read and simulate the EnergyPlus in the requested period. The design requires an optimization algorithm to evaluate different scenarios and present the results. For this purpose, jEPlus+EA software is used, which according to the NSGA-II algorithm and the input of optimization values of this algorithm by the designer, the modes created by jEPlus Beam evaluation and diagram, and the objective functions of the answer, as well as the corresponding decision-making parameters [26]. Using this method, EnergyPlus software can optimize all building design parameters. Fig. 1 shows the flowchart of the modeling and optimization procedures.

Table 2. Linear relationships of control modes.

Cooling/heating mode	Incident solar radiation (I) (W/m^2)	Slat angle (°)
Cooling	< 100	90
	100 to 700	$-0.15I + 105$
	> 700	0
Heating	< 100	0
	100 to 700	$0.15I - 15$
	> 700	90
No cooling or heating	All	0

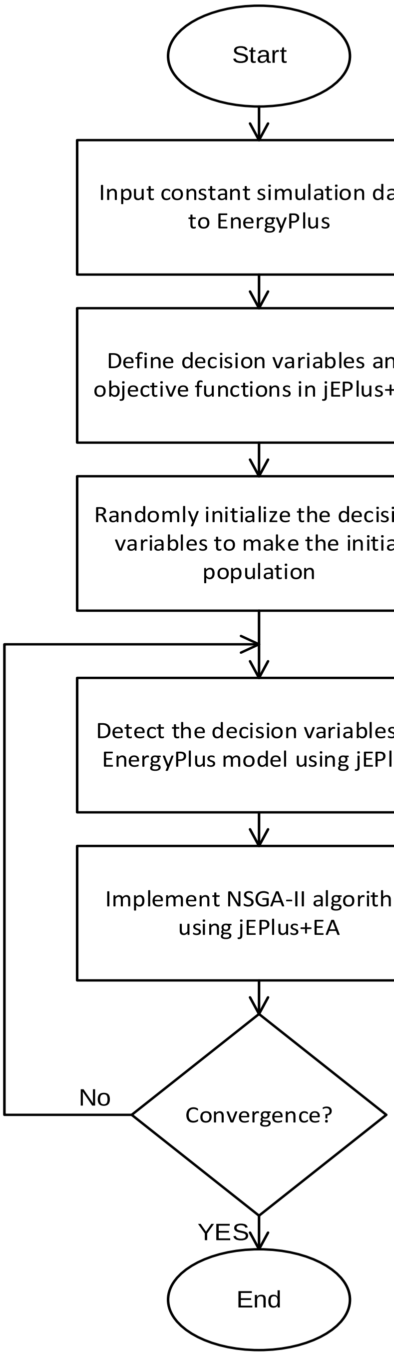

Fig. 1. The flowchart of the modeling and optimization procedures considered in this study.

3. Modeling Materials

3.1 Model Specifications

To study the control strategy on the slat angle of blades as well as smart window and optimization of shading architectural parameters and control activation thresholds on a building, a new method was obtained in the field of building energy simulation based on one room of a multi-story building in Tehran. It is assumed that the room is located on one of the middle floors of the building so that all of its envelopes including walls, ceiling, and floor are internal ones without heat transfer except the wall with a window which is external. Figure 2 shows the room and of course, the building that includes the room is displayed.

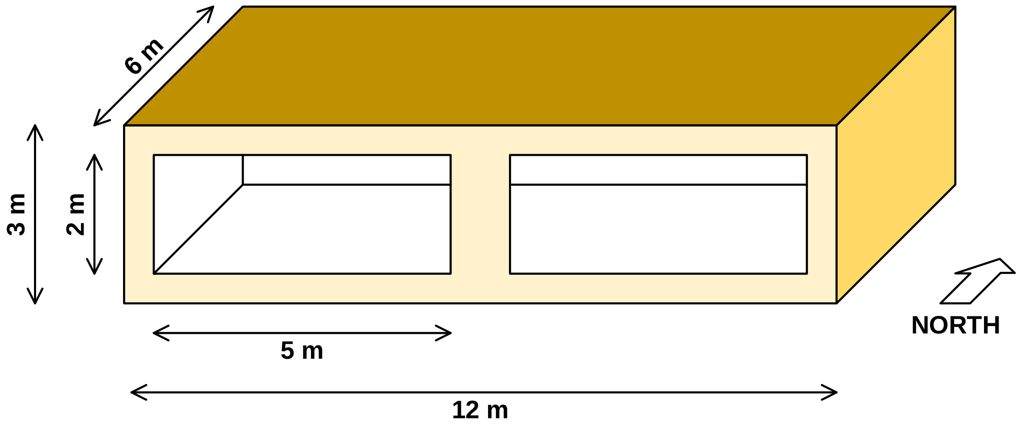

Fig. 2. The shape of the building model.

Table 3. Building material specifications [39].

Element	Properties	Unit	Value
Interior wall	Thickness	m	0.048
	Specific heat capacity	J/kgK	2180
	Total heat transfer coefficient	W/m^2K	2.581
Exterior wall	Thickness	m	0.1
	Specific heat capacity	J/kgK	790
	Total heat transfer coefficient	W/m^2K	0.7
Floor/ceiling	Thickness	M	0.1207
	Specific heat capacity	J/kgK	1430
	Total heat transfer coefficient	W/m^2K	1.45

The room has length, width, and height of 12, 6, and 3 meters, respectively, which are typical dimensions of large office rooms in Iran. Besides, according to Iranian National Building Regulations of has been used for building materials. The specifications of these materials are shown in Table 3 [39].

Also, simulate the south-facing wall of the building includes two windows with shadings of the type of internal blind with a moderate amount of internal reflection, which in the initial state according to the temperature inside the open room means that the slat angle of the shading blades is equal to zero degrees or closed means the slat angle 90° shading blades, with the same dimensions of 2×5 m2 and with double glazing of 3 mm and also 6 mm air between the layers, which transfers heat with the outside air and is exposed to the sun. The room is equipped with a packaged terminal heat pump air conditioner (PTHP) the capacity of which is automatically calculated considering the hottest and coldest days of the year. PTHP heating and cooling setpoints, respectively 22 and 26°C, respectively, in the working hours of Iran, i.e., Saturday to Wednesday from 8 am to 4 pm. Also, to calculate the thermal comfort, the Fangar method has been used, which is a program for covering the insulation of clothes and the airspeed in the two seasons of winter and summer is given to the software according to the ASHRAE 55 standard [34]. Thus, in the warm seasons of the year, the insulation level of clothes is 0.5 and the room airspeed is 0.2 m/s, and in the cold seasons of the year. The insulation level of the clothes is 1 and the room airspeed is 0.5 m/s. In the mentioned room, for daylighting control, two daylight sensors with a designation point of 500 lux and a lighting system of 10 watts per square meter have been considered. These two sensors are located in the middle of the room and at 0.8 meters above the floor (desk height) [28].

3.2 Climate regions of Iran

In this paper, the city of Tehran with a cold semi-arid climate [40] is considered whose general specifications are shown in Table 4.

Table 4. General specifications of Tehran city.

Latitude	Longitude	Elevation (m)	HDD	CDD
35.7°N	51.4°E	1219	1810	865

3.3 Optimization Method

Manually changing the design parameters and simulation of each model to find the best answer is practically impossible. Because there are so many scenarios due to the multiplicity of design parameters, and also if this method is used, the researcher will only be able to provide a very small number of solutions to achieve the optimal value. Therefore, it is necessary to use a method in which the computer finds a possible answer among the various scenarios of design parameters using optimization algorithms and presents it to the designer. Due to the separation of emulator software and optimizer software, it is necessary to establish a kind of communication between the two software. So, the optimizer software executes the simulator software by a series of code files and then calls the decision parameters defined by the designer from the software and changes them within the allowed range of their changes. During these steps, the optimizer software evaluates the answers of the objective functions using its optimization algorithm and continues this loop until the conditions defined for the optimization algorithm are satisfied to provide the optimal values. These steps are called simulation-based optimization processes [41, 42].

Considering that the main goal of this research is to reduce the total annual electrical energy consumption of the building while increasing the thermal and visual comfort of the residents, the one-objective optimization approach is not desired. The annual total energy consumed by lighting, heating, and cooling systems, the annual average PPD, and the annual average DGI are considered objective functions, which are calculated only during working hours. In most cases, reverse the effects of the decision variables objective functions. For example, in the cold seasons when a building needs to be heated, the lack of shading during the day helps reduce the energy consumption of HVACs and lighting systems, while also causing visual discomfort. In the same season during the nights, the use of insulating materials for the shading devices can reduce the electricity consumption of the heating system. In the warmer seasons, even if shading reduces the HVAC system energy requirement, it prevents natural light from entering and increases the energy consumed by the artificial lighting system. In this case, changing the parameters to reduce the total electricity consumption may cause thermal or visual discomfort.

3.3.1 Multi-objective optimization approach in slat angle control strategy

To compare the results of this strategy, two basic scenarios can be considered. In this way, it was output from EnergyPlus software, once without shading and in another case with shading, so that the slat angle of the shading blades is fixed and equal to 45°.

3.3.2 Multi-objective optimization approach for smart window control strategy

To compare the results of this strategy, the initial state is considered as a window without a smart window and in the case of a double-glazed window, and output from EnergyPlus software.

4. Results and Discussions

In multi-objective optimization problems, we are dealing with more than one function, so the answer to the problem is not a single one, and a set of answers are presented as optimal points. This set, which, while not being superior to each other, is superior to other responses, is called the Pareto optimal front. All points on the Pareto front can potentially be considered optimal points for the system under study. There are a lot of ways to determine an optimal point among the optimal and unsuccessful points obtained from solving multi-objective optimization problems. To determine the optimal point, we need multiple-criteria decision-making (MCDM). Decision-making is a process that includes the correct expression of goals, determining different and possible solutions, evaluating their feasibility, predicting and evaluating, and comparing the results of the implementation of each solution and the final choice of a solution to achieve the goals are desirable.

The three-dimensional Pareto front of the NSGA-II optimization is presented in Fig. 3 for the slat angle control strategy. As shown in the figure, the optimization procedure offers a variety of results, with each point from the front being an optimal solution. To find the final optimum solution between Pareto front points, in this study, the weighted sum method [43-45] is used as a decision-making method using Eq. (3):

$$f_{ws}(x)=\sum_{i=1}^{3}a_i\frac{f_i(x)-f_i(x)^{min}}{f_i(x)^{max}-f_i(x)^{min}} \quad (3)$$

where $f_i(x)$ are the objective functions including annual electricity consumption, PPD, and DGI. In the same way, $f_i\ (x)^{min}$ and $f_i\ (x)^{max}$ are the minimum and maximum of each objective function, respectively. a_i are also the weighting factor of the objective functions. Due to the greater importance of building energy consumption, the main focus in choosing the final solution is placed on the first objective function and the factor of its effect in choosing the optimal solution is selected more than thermal and visual comfort indicators. Also, the weight effect coefficient of thermal and visual comfort is considered the same. So:

$$a_2=a_3=\frac{1-a_1}{2} \quad (4)$$

In this way, a multi-objective optimization problem becomes a single-objective one in which $f_{ws}(x)$ is minimized and its only decision parameter is a_1.

As a result, to select the optimal point for each of the decision-making variables for both strategies, to reduce the total energy consumption, the value of a_1 is considered equal to 0.9. Since the values of thermal and visual comfort after optimization are in their desired range, it means that the value of DGI is less than 22, and PPD (%) is less than 10%, their impact factor is considered equal to 0.05 [22]. Tables 5 to 7 show the optimal point and its difference from the initial value in each strategy.

According to Table 8, to optimize the decision variable in the smart window strategy, based on the program code in the simulator software, at any temperature, it determines the most optimal type of smart window with the window structure index (differences in thermochromic window structure).

Table 9 also points out the differences between the two samples of thermochromic windows, which only in the structural part of this type of window, there is a difference that can be generalized to other types of this type of window.

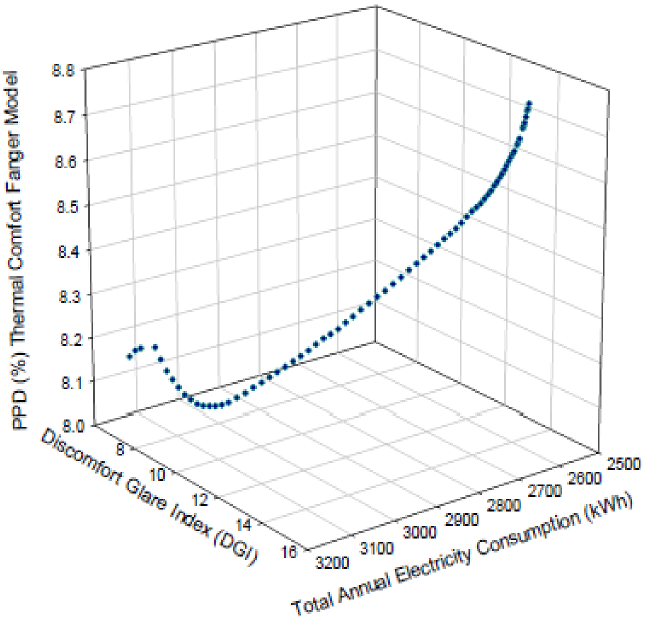

Fig. 3. Pareto fronts of three-objective optimization for the control strategy of blades slat angle.

Table 5. Results of three-objective optimization for the blades slat angle control strategy.

Objective function	**1st initial case: Without shading**	**2nd initial case: With 45° slat angle shading**	**Optimal case**	**Improvement (%)**	
				Relative to 1st initial case	**Relative to 2nd initial case**
Total annual electrical energy consumption (kWh)	2839	2586	2282	19.5	11.7
PPD (%)	17.0	8.7	8.1	52.4	6.4
DGI (-)	28.1	13.8	7.4	73.9	46.6

Table 6. Results of three-objective optimization for the smart window control strategy.

Objective function	**Initial case**	**Optimal case**	**Improvement (%)**
Total annual electrical energy consumption (kWh)	2739	1952	28.7
PPD (%)	18.6	8.1	56.5
DGI (-)	28.1	18.8	33.1

Table 7. Results Optimum decision variables in the blades slat angle control strategy.

Decision Variables	**Limits**	**Initial case**	**Optimal case**
Slat angle (°)	Lower	45	43
	Upper		70
Incident Solar Radiation (I) (W/m^2)	Lower	-	90
	Upper		234

Table 8. Results optimum decision variables in the smart window control strategy.

Activation temperature (°C)	**Structure index (-)**
26	25
28	31
30	33
32	35
34	37
36	39
38	41
40	43
42	45
44	50
47.5	55
52.5	60
62.5	65
72.5	70
77.5	75
82.5	80
85	85

Table 9. The difference between the two types of thermochromic windows.

Thermochromics window type	**Structure**
TCwindow_41	Clear 3mm Air 6mm WO18RT41 Air 6mm SB60Clear3PPG
TCwindow_45	Clear 3mm Air 6mm WO18RT45 Air 6mm SB60Clear3PPG

The main purpose of this research is to present a new solution for the use of controlled shading blinds to not only reduce the overall annual energy consumption of the building but also to maximize the thermal and visual comfort of the occupants. Due to the excessive complexity of building energy calculations and, more importantly, the high number of calculations, the use of powerful computer simulation software to perform simulation, control, and optimization processes is of particular importance. Therefore, in this study, after the initial simulation by the accurate and powerful software of EnergyPlus, the parametric study and optimization of the relevant objective functions according to the control parameters and decision-making architecture were performed and the results are displayed as Pareto fronts and tables for each control strategy.

By evaluating and comparing the results of three-objective optimization with the initial values in the case that the slat angle of the shading blades is fixed and equal to 45° in the blades slat angle control strategy shows that the total annual energy consumption of the building up to 11.74 percent, DGI visual discomfort index up to 6.4 percent And PPD thermal discomfort index decreased to 46.6% and in the smart window control strategy whose initial state is double glazing, the results also decreased by 28.73, 56.50 and 34.05%, respectively. The results clearly show how the correct choice of architectural parameters, smart window material, the slat angle between the shading blades, and the amount of sunlight can prevent heat loss while providing thermal and visual comfort to the building's occupants.

In most buildings, shadings are activated automatically by the people present, simply to prevent glare. This paper showed how control strategies can be effective in reducing consumption and increasing comfort. Carefully in the results, it can be easily achieved that the effect of using the shading on the functions of total energy consumption, visual comfort, and thermal comfort is by no means predictable and in many cases contradictory. In cold climates and well-lit windows, the use of shading reduces the DGI, but due to the increased heating load of the building in the cold season, the total energy consumption is increased, and also due to the decrease in temperature in winter, thermal comfort may be lost.

It can be said that usually the type of window material and the slat angle of the shading blades are not considered, while according to the study done in the previous chapter, it was determined how much the effect of changing the two on the target functions is high and the need to find the optimal point becomes clear.

5. Conclusions

In this research, to focus more on control strategies, the simulation was carried out using EMS, which is a powerful tool for building energy simulation software titled EnergyPlus. Using coding, objective functions and selected decision-maker parameters of the simulator software were specified to the optimizer software, jEPlus+EA. EnergyPlus was coupled with jEPlus+EA through the NSGA-II algorithm to optimize the results. To evaluate and monitor accurately, control strategies and optimization operations are implemented in a typical room located on the middle floors of a building, and the results of simulations, shading control, and multi-objective optimization of building energy performance have been evaluated in the climate of Tehran. Slat angle, solar radiation, and the material of the smart window were selected as decision variables in three-objective optimization. Also, the total annual energy consumption of the building and the thermal and visual discomfort index are considered three objective functions of the research, which should be minimized. Comparison of the results of the three-objective optimization with the initial values, when the angles of slats are constant and equal to 45°, showed that the total annual energy consumption, DGI visual discomfort index, PPD thermal discomfort index reduced up to 11.74%, 6.4%, and 46.6%, respectively. In the smart window control strategy, the reductions were 28.73, 56.50, and 34.05%, respectively, in comparison with the double-glazing window. The results clearly show how the correct selection of architectural parameters and control strategies for shading and their activation set points in different weather conditions can greatly prevent energy losses while providing the thermal and visual comfort of the building occupants.

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