Optimum Dimensions of Windows to Improve Daylight and Energy Consumption of Educational Buildings in Hot and Dry Climate, A Case Study of Yazd City

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Today, reducing energy consumption is one of the global concerns of preserving resources and the environment. The building industry is the main consumer of energy among all industries, so reducing energy consumption in this sector is important. This research aims to optimize the dimensions of windows in educational buildings to improve the quality of daylight and energy consumption, and for this purpose, one of the most important parameters, i.e. window-to-wall ratio, has been evaluated. Due to the parametric nature of the simulations, the software Rhino-Grasshopper plugin has been used to build the initial parametric model. Honeybee and Ladybug plugins have been used to simulate energy and light due to the use of the validated Energy Plus engine for thermal calculations. The results showed that the energy consumption of the building improved by about 12%, and the useful brightness of daylight improved by about 38% after optimization. The optimal size of the window-to-wall ratio for classrooms that received southeast and northwest light was about 25%, and for classrooms that received northeast light, about 20%.

Keywords: *Educational Buildings, Reducing Energy Consumption; Hot and Dry Climate; Window Dimensions; Daylight.*

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1. Introduction

In recent years, increasing use of energy resources has reduced national energy re-sources and increased environmental pollution caused by burning, which has adverse consequences such as climate change, global warming and ecosystem change [1]. Due to the limitation of energy resources and extensive environmental effects, the use of structures that reduce energy consumption has become particularly important. [2,3] According to statistics, the energy consumption index in Iran is about 4 times the global average, which will have adverse consequences such as depletion of national resources and drought crisis. Among energy consumers, the construction sector, as one of the major consumers, accounts for 40% of the total energy consumption of the country [4]. In addition, in Iranian buildings, 34% of the share of electrical energy belongs to lighting consumption [5]. In the construction sector, educational use accounts for a significant portion of energy consumption. In addition, the quality of daylight has a great impact on the visual quality of educational spaces [6]. The annual average energy consumption in educational buildings is more than 160 kWh/m2, while in developed countries this index is about 65 kWh/m2 [7]. Today, with the increase in school construction statistics and lack of attention to climatic considerations and the lack of use of architectural solutions to reduce energy consumption has caused schools to pay exorbitant costs to provide their energy [8]. Meanwhile, due to the type of users and the time occupied by the space, which is only nine months of the year, the school building has a high potential for energy efficiency during design and construction as well as operation [9]. In this regard, improving the condition of the building shell is an effective step to reduce the energy consumption of the building. Also, one of the effective ways to control and maintain comfort and reduce energy consumption is to use daylight. The importance of using daylight in educational spaces is very significant because it increases the efficiency of students [10,11]. Therefore, it is important that buildings use low-energy structures throughout their operational life cycle [12]. Window panels have a significant effect on the energy performance of the building and provide thermal comfort and the quality of the visual environment [13]. They perform a variety of important functions in buildings, including: connecting to the external environment, providing thermal comfort, lighting quality, and air conditioning [14]. Besides, seeing open views through windows is a special ad-vantage for all buildings [15]. However, a significant part of the wasted heat takes place through the windows [16]. Also, another important effect of daylight is due to its beneficial psychological effects and improving the health and well-being of buildings. [17–20]. If daylight is integrated with lighting control systems, they can reduce electricity consumption by 20% [21–23]. A side benefit of daylighting is the reduction of cooling costs by reducing the heat generated by the lighting system [24,25]. The amount and quality of daylight is mainly influenced by the placement and dimensions of the window [26–28].

However, incoming solar radiation can be controlled using shading systems [29–32]. Also, increasing daylight in space will reduce the amount of electrical energy consumption in the lighting sector, which will affect the amount of energy consumption of the entire building [33].

The main objective of this research is to optimize window dimensions with the approach of reducing energy consumption and optimal access to daylight in educational buildings in Yazd city, representing a hot and dry climate. The present research also has the following sub-objectives:

- Obtaining the optimal window length to width ratio and the transparent to opaque wall ratio in the hot and dry climate of Yazd
- Implementing a parametric model to simulate energy and daylight and optimize the windows of educational buildings
- Optimal percentage of windows in different facades of an educational building in a hot and dry climate

Although much research has been conducted on the optimal dimensions of openings in all climates, the simultaneous calculation of daylight parameters and energy consumption in an educational building, taking into account the importance of daylight quality in educational buildings, is one of the innovative aspects of this study. Especially since optimal energy consumption and achieving daylight quality are important factors for educational buildings in hot and dry climates. This research suggests optimal characteristics of a building element. Using different measurement tools and plugins can improve the results. Other research variables such as psychological concepts and daylight effects can limit some of the results.

2. Literature Review

Numerous studies have explored the impact of window dimensions on natural light and energy consumption. Lartigue et al. noted that natural light cannot be considered separately from thermal comfort [34]. Melendo and Roche demonstrated that proper window design, considering both lighting intensity and temperature, can significantly reduce cooling loads and energy consumption [35]. Montaser Koohsari et al. highlighted that energy consumption and daylight efficiency are crucial determinants of window size [36]. Simulations by Dabe and Dongre using Ecotect and Daysim software revealed the significant effect of window size on visual and thermal comfort in hot and dry climates [37].

Li et al. found that to optimize daylight gain and energy efficiency, the Window-to-Wall Ratio (WWR) should be at least 25% for west, east, and south facades, and 50% for north facades [38]. Akhtarkavan and Shafiei's study in Isfahan showed that while increasing window size reduces the use of artificial lighting, an excessive increase in window size has a minimal effect on electricity consumption [39]. Barzanouni et al. determined that the lowest energy consumption occurs with a WWR of 63% for the south, 47.6% for the north, and 31.7% for the east and west walls [40]. Khanmohamadi et al. identified a WWR of 30% as the optimal ratio for achieving daylight [41].

Heirani Pour et al. (2021) examined optimal window dimensions for south and north facades, suggesting that the optimal WWR for the south façade is 24% [42]. In various countries, the optimal Window-to-Floor Area Ratio (WFR) for daylight is 10% in southern Europe and 25% in northern regions, with a WWR not exceeding 50% [43]. Iran's earthquake regulations recommend keeping WWR values at a maximum of 20% for optimal light and heat performance [44]. Ochoa et al. investigated the appropriate window-to-wall area ratio for visual comfort, light, and heat in residential buildings with different façade orientations [45].

Goia et al. (2013) suggested an appropriate WWR of 35-45% for the south wall [46]. Scott et al. (2009) found that the optimal WWR for light reception and reduced energy consumption is 10%, regardless of latitude and glass type [47]. Montaser Koohsari et al. (2014) indicated that the optimal WWR for the southern façade is between 18% and 29% [48]. Alwetaishi (2017) studied various WWRs in different climates in Saudi Arabia, suggesting a 10% ratio for hot-dry and hot-humid climates, and 20% for temperate climates. The light penetration depth should be 1.5 to 2.5 times the height of the window above the floor [49].

Horizontal and square windows under the ceiling are preferred for moderate brightness and less light around the windows, proving to be better options according to several studies. Design recommendations include a minimum window height of 1.25 meters and a minimum width of half the wall width, with the living room window area being at least 7% of the room space [43]. Heirani Pour et al. (2021) suggested optimal window dimensions for various cases, recommending a WWR of 24% for the south façade without shading devices, 19% with shading devices, and 4% for the north façade [42].

3. Methodology

This study aims to balance ambient light quality and energy consumption in a hot and dry climate, with Yazd chosen as a suitable example and educational use case. Rhino, a 3D commercial graphics tool, is employed for this purpose, leveraging its algorithmic environment called Grasshopper. Grasshopper supports generative algorithms and parametric processing, with various functional plugins, the most significant being Ladybug Tools.

In this study, version 1.4.0 of the Ladybug Tools plugin is used. Ladybug Tools is a set of building performance simulation tools offering features like energy simulation, thermal load analysis, daylight evaluation, and natural ventilation assessment.

The Ladybug plugin specifically analyzes and reads Energy Plus (EPW) approved weather data files, presenting results in 2D and 3D graphics. It utilizes the Energy Plus, Radiance, and Open Studio engines to simulate the building's energy performance and daylighting, ensuring precise results based on the input data.

EnergyPlus has undergone extensive validation to ensure its accuracy and reliability [50]. According to Witte (2001), formal independent testing has been an integral component in the development of EnergyPlus [51]. This testing includes analytical, comparative, sensitivity, range, and empirical tests [51]. Published test suites, such as ANSI/ASHRAE Standard 140-2001 and IEA SHC HVAC BESTest, have been applied to take advantage of well-defined, reproducible tests. Comparative testing has shown good agreement with established simulation programs like DOE-2.1E, BLAST, and ESP. Additionally, empirical testing using real-world data and experiments has validated the simulation results. Queiroz et al. (2020) conducted a performance-based design validation study on EnergyPlus for daylighting analysis, comparing it with the Radiance simulation engine [52]. The results showed that EnergyPlus classified solutions similarly to Radiance, with errors within a 20% margin [50-52]. The extensive validation process ensures that EnergyPlus provides accurate and reliable simulations, making it a trusted tool for building energy analysis. The combination of analytical, comparative, sensitivity, range, and empirical tests, along with standardized test suites, supports the validity of EnergyPlus as a robust simulation tool.

Table 1. Energy Consumption Index in Schools [55]

Condition	Based on square meters of infrastructure		Based on the number of students	
	Good	Common	Good	Common
Fossil fuels	12	16/5	76	107
Electricity	20	28	126	167

Table 2. Architectural solutions to reduce building energy consumption [57]

Design Strategy	Heating	Cooling	Natural Ventilation	Daylight
Orientation	●	●	●	●
Shape and Form	●	●	●	●
Placement of Spaces	●	●	●	●
Window to Wall Ratio	●	●	●	●
Canopy	●	●	●	●
Window Size and Location	●	●	●	●
Thermal Mass	●	●		
Air Penetration	●	●	●	
Thermal Insulation	●	●	●	

The efficiency of a building in saving energy depends on the shape, direction and size of the windows [53, 54]. Today, energy consumption in buildings is a serious challenge, especially in schools and educational spaces (Table 1). Architectural solutions (Table 2) can be applied to achieve greater energy efficiency for the entire building life cycle [56].

Daylight is one of the factors affecting the quality of learning. Therefore, it is very important to pay attention to the surfaces of the openings and their extensions such as canopies. In some cases, even paying attention to the arrangement of walls, interior doors and windows affect this important matter [58]. The efficiency of daylight in spaces depends on three factors [10]:

1. How to use daylight through the outer shell
2. Physical and geometric characteristics of the surfaces of the openings
3. Physical and geometric characteristics of the space

Also, in order to optimize the light in educational spaces, factors such as: the amount of light according to the type of activity, reflectivity of surfaces and the amount of difference in light intensity of surfaces, light distribution in space should be considered [59]. Proper orientation of the building can significantly reduce the energy consumption of the building. Figure 1 shows the optimal orientation of the building in hot and dry climates.

Daylight is a combination of direct and indirect sunlight during the day that includes direct light, scattered light, and light reflected from the ground and other surfaces (Figure 1).

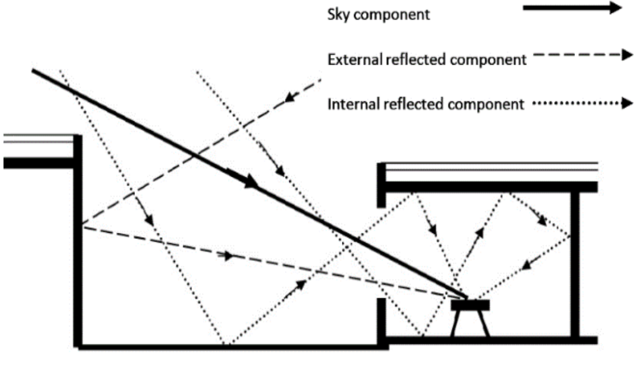

Fig. 1. Daylight factor components [60]

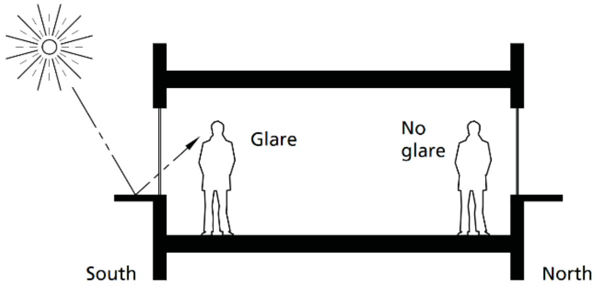

Fig. 2. Direct South Light Glare vs. Glare-Free North Light [63]

Light intensity is one of the important cases for studying daylight in indoor spaces and includes the amount of light flux (lumen or luxury) that is received through the surface (square meters) [61]. The amount of required light determines the material of the glass, the location of the shutters, their dimensions and shapes [62].

Important points in designing the lighting of educational spaces are: maximum use of daylight, placement of classrooms on the north and south sides, preventing severe re-flections of interior surfaces, preventing light entering from the west, reducing glare, preventing direct sunlight or at least light entering From the left side of the students and using ceiling skylights to scatter light in the classroom. Also, the required level for lighting the windows is one fifth of the whole class space, and if the width of the class is more than 720 cm, it should be placed openings on both sides of the classroom. Daylight factor in classrooms should not be less than two percent [13]. The factor of daylight is defined as the ratio of light inside the space to the light of its outside and in cloudy sky conditions [61]. In other words, daylight factor is the sum of direct radiation reflected from internal and external surfaces that can be calculated for a point or the average of the whole space [60]. Glare is one of the important factors in improving daylight and includes con-trolling the difference in brightness of interior surfaces [59] and controlling it causes visual comfort of the environment by creating a balance between direct and indirect lighting [60] (Figure 2).

Stunning control strategies include not placing windows at points of visual focus (for example, near the classroom boards), bright colors for ceilings and walls to scatter light throughout the classroom, and the use of awnings and curtains [60]. The window, as the weakest part of the building shell, provides natural visibility, light and ventilation, and directly affects thermal comfort and energy consumption. The most widely used types of windows in educational spaces include sunny, skylight and attic windows. Sunny or solar windows face south and should be controlled in terms of creating light contrast and glare. Skylights work well to collect daylight. Even when the sky is cloudy, the amount of light entering is three times the amount received from the sky-lights and vertical windows. One of the advantages of these windows is the reduction of energy consumption in the lighting sector, but, heat loss in winter and heat transfer in summer are its disadvantages [62]. The use of skylights provides uniform light. The greater distance of this window from the floor, the less dazzling will be [66, 67]. The dimensions and area of the window, in addition to affecting the amount of light, also affect the amount of cooling and heating load in the building. Therefore, in deter-mining the appropriate dimensions of the window, in addition to the quality of space lighting and saving energy consumption, lighting, cooling and heating should be considered. Among the different facades of a building, the translucent surfaces on the southern facade show better thermal performance. These surfaces help to absorb the sun's radiant energy and provide space heating in the cold months of the year. The depth of light penetration and the improvement of light uniformity in the interior space depends on the height of the window and its distance from the ceiling and floor. Proper design and se-lection of the area of permeable surfaces, in addition to providing light to interior spaces, reduces the amount of heat loss through the building shell. This rate should not exceed 35% in educational spaces [15]. The optimal ratio of window surface to wall should be designed in the early design stages and in coordination with the form, orientation and dimensions of the window. This ratio should reduce the total energy required for heating, cooling and lighting [65]. The ratio of window to wall surface affects the energy consumption of the building and the comfort conditions of users by changing the rate of heat transfer from the shell, solar heat radiation, unwanted air leakage and received day-light. Among the items studied in determining the optimal ratio of window to wall ratio, solar gain, visibility and heat transfer, as well as climatic conditions [66].

In this study, given the research objective, certain parameters such as materials, floor height, etc., are fixed, while some parameters, such as the window-to-wall area ratio and the depth of the shading device, are variable. Naturally, the optimization of these variable parameters is very important considering the two objectives under review. The first variable parameter in this study is the integration or non-integration of the window. The subsequent variables pertain to the window-to-wall area ratio, with several types of window-to-wall area ratios considered due to the varying placement of classrooms and office rooms.

Regarding the classrooms, out of the six classrooms on the ground floor, five are aligned vertically, allowing for light reception from two directions. Other directions will not have windows by default. Additionally, one classroom has a different orientation than the others, creating a new parameter. Similarly, for the office rooms, which can receive light from two sides, two variable parameters are considered. In total, this study includes seven variables. Furthermore, the presence and absence of shading devices with different depths are examined. Considering the northern orientation and the building's orientation, it is anticipated that the need for shading will be minimal, and this will be further investigated.

After identifying the input and output variables, optimization was performed. This optimization includes 30 generations, with each generation containing 50 genes. The building's energy consumption and the beneficial daylight illuminance are set as target parameters, which determine the type and window-to-wall area ratio of the main spaces (classrooms and offices) and the need for shading devices. It is worth mentioning that due to the heavy simulation and optimization process, the research objectives were only applied to the classrooms and offices on the ground floor.

In this study, the target values were assessed annually. In Image 17, the overall optimization algorithm process is illustrated, showing that 1,500 options were generated and reviewed, from which a few options were chosen as optimal. It is important to note that the optimal option does not necessarily optimize each individual parameter but instead aims to reach an optimal midpoint for both objectives.

The simulation and optimization process was performed algorithmically. Initially, a 3D model was created, and then the windows were applied as constraints. It should be noted that in this study, the lighting schedule was created based on lighting analysis and used in the energy simulation process after each analysis. This reduces the lighting load since the required lux for the space is provided by daylight when available, and any excess is supplemented by artificial lighting.

The present study deals with the design and evaluation of a 12-grade one-year elementary school (Figure 3).

The selected site is located in the east of Yazd city, in the old part of the city. To evaluate the optimal orientation of the building, Ecotect Software has been used based on three cold months and three hot months of the year. In the climate of Yazd, the optimal orientation is to the south with a deviation of 2.5 degrees to the west (Figure 4).

The calculation of daylight and energy performance is conducted using a comparative tool designed to evaluate and optimize these parameters. This tool analyzes multiple scenarios and benchmarks them against established criteria to determine optimal performance.

Optimal performance thresholds are defined based on a comprehensive set of criteria, including energy consumption metrics, beneficial daylight illuminance levels, and predefined comfort standards. By employing this comparison tool, we are able to systematically identify the best-performing configurations and recommend solutions that balance energy efficiency with optimal daylight utilization.

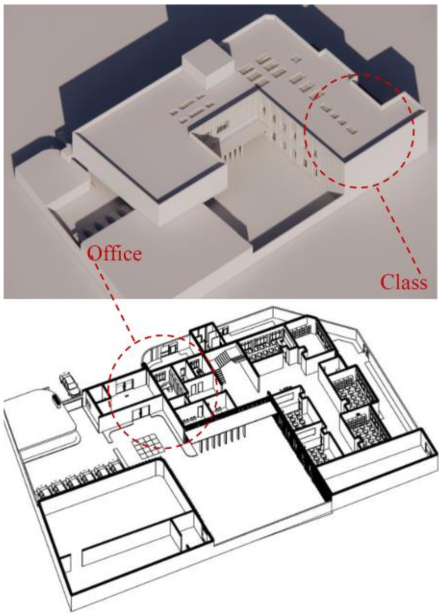

Fig. 3. The simulated perspective of the case study

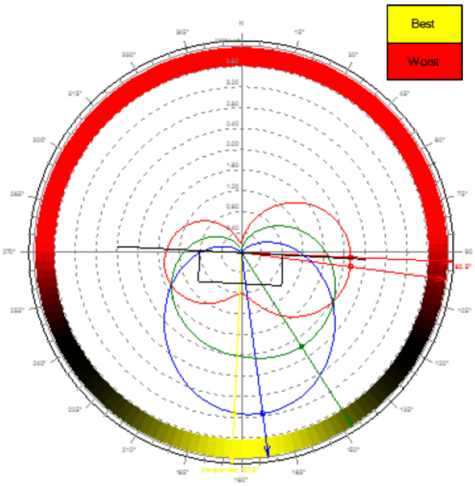

Fig. 4. Optimal orientation

4. Results

Since in this study, Honeybee Tools plugins were used, the simulation was also performed parametrically. Therefore, first the use of each space is determined and then each use and section has changed to a thermal zone. It should be noted that the thermal zoning of the building is not necessarily in accordance with the architectural plan be-cause sometimes several spaces have the same thermal conditions and there is no need to divide the zoning. For example, in this study, the corridor and the stairwell have considered in one zone. On the other hand, in each zone, it must be determined whether it is controlled or not. In fact, there is the user in controlled spaces and it is needed that com-fort conditions be provided (met) by mechanical or natural systems. If comfort conditions are not provided, that space is considered uncontrolled. So, all the main spaces of the school have been considered as the controlled space. Building simulation can be in order to reach the optimal point of receiving daylight from two aspects of energy and daylight. Because, receiving maximum sunlight increases the cooling load of the building and this increases the energy consumption of the building despite reducing the lighting load of the building. Therefore, the optimal point of this amount should be investigated (studied). Due to the usefulness of the useful lighting parameter, daylight is the criterion for evaluating lighting performance. Daylight parameters provide a useful tool for determining the potential of receiving daylight in a space, and the optimality of this issue can reduce energy consumption [64]. The optimization of the research findings was done after identifying the input and output variables. In this optimization, there are 30 generations and, in each generation, there are 50 genes. Intensity of building energy consumption and useful brightness of daylight are identified as target parameters.

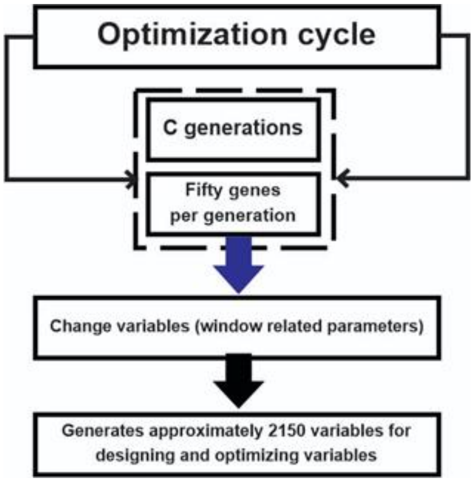

Fig. 5. Optimization process in the simulation cycle

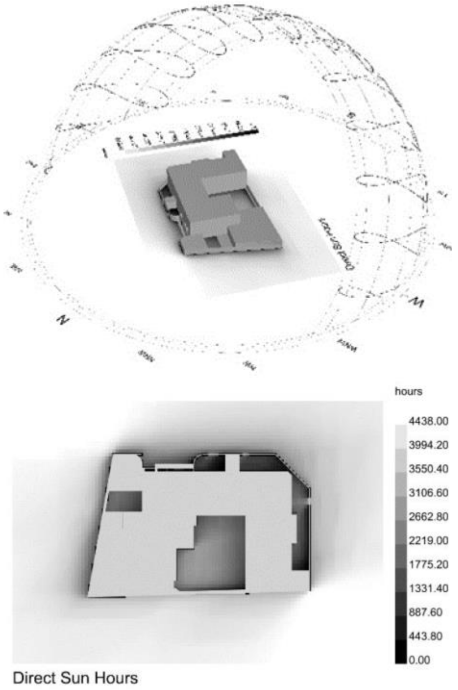

Fig. 6. Receiving direct (sun) radiation and shading study

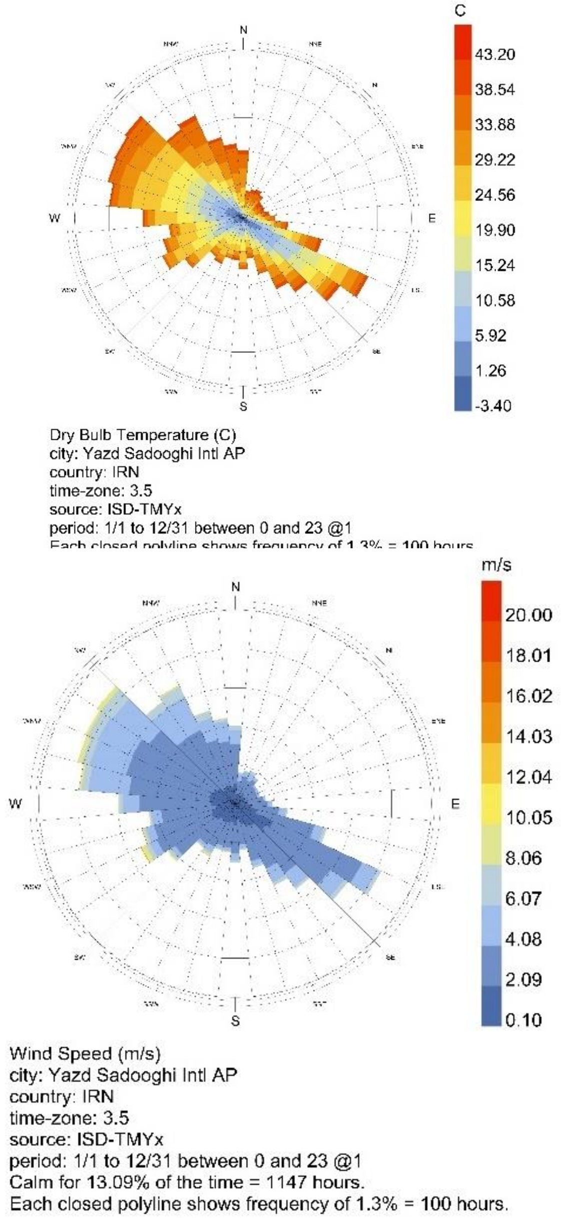

Fig. 7. Annual flowering by temperature and speed

It should be noted that due to the weight of simulations and optimizations, the objectives of the research have been done only for classrooms and ground floor office space. Figure 6 shows the general trend of the optimization algorithm in which 1500 options generated and examined, from which several options are selected as the optimal option. Of course, it should be noted that the optimal option does not mean that each parameter is optimal, but it means reaching the midpoint of both goals (Figure 5).

The studied building is examined based on the shading of the whole year in the period of 7 am to 4 pm, in figure 6. Two other effective parameters (wind and radiation) have been effective in the design and arrangement of spaces, which is shown in Figure 10 of the city of Yazd (Figure 7).

In fact, the two parameters of radiation and wind can have different effects on the environment. By examining this issue, we can see what effects the presence or absence of each parameter will have in design process. However, it should be noted that wind and radiation cannot be completely prevented. But, these two natural factors can be used optimally (Figure 8).

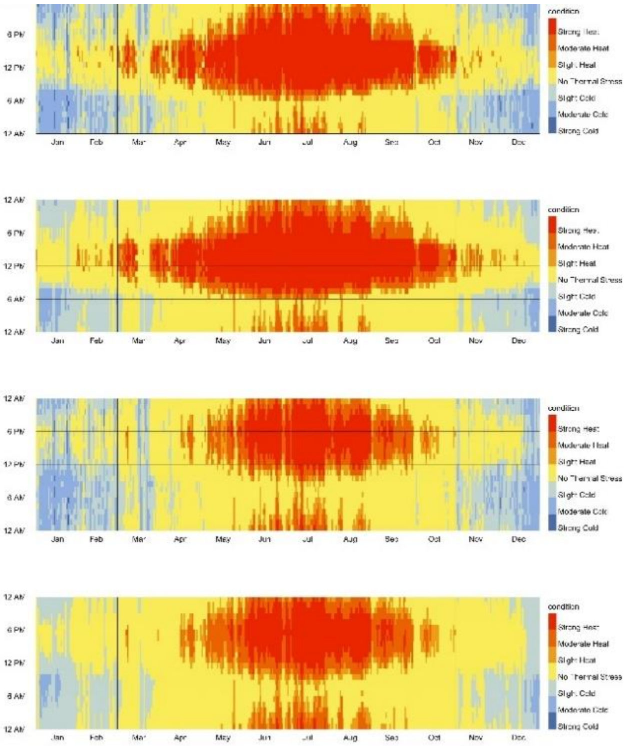

Fig. 8. Investigation of the presence and absence of radiation and wind in creating ambient thermal comfort

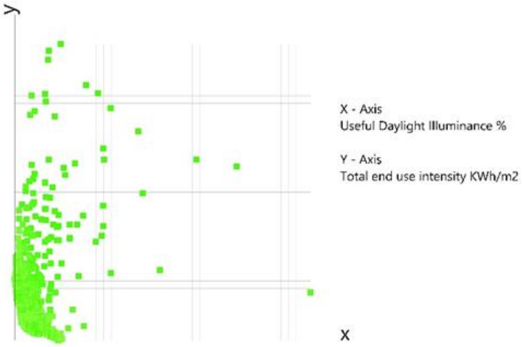

Fig. 9. Pareto chart of multi-objective optimization

Figure 8 shows respectively, the thermal comfort, with assuming different states of the existence or the absence of wind and radiation. It can be clearly seen that due to the prevailing summer wind with high temperature and relative speed is low and does not provide comfort for open environments. Figure 10 shows Pareto two-dimensional target values for the solutions produced. Pareto chart is used to show the optimal values and the distribution of data among the targets.

In Figure 9, the x-axis represents the useful brightness of daylight and the y-axis represents the intensity of energy consumption. The closer these points are to the axes of the graph, the closer they are to the optimal solutions of the objective function, and when the points are closer to the origin of the coordinates, they are actually closer to the optimal option of the whole research.

Figure 10 shows a range of optimal solutions. These diagrams show how the optimization process is done. In the standard deviation diagram, the more simulations are done, the closer the bases get to each other and move to the blue color, which indicates optimization. Also, the optimal answer for discussing the intensity of energy consumption is between 32-36% to 44-48% and for useful daylight is between 39-43% to 44-59%. Standard deviation diagrams can help in validating the objective functions because the process of optimizing the functions can be clearly examined, but in the continuation, other solutions are also examined to validate the results.

Figure 11 shows the process of changing each of the objectives to optimize the input parameters. In this diagram, considering that the trend of changes and fluctuations is downward, it can be concluded that the answers are moving towards optimization, and if there is a sufficient and appropriate time and system, better results can be achieved. It should be noted that if the trend line is ascending, it means that no improvement is achieved and the answers are not optimized, and if it is a smooth and parallel line, it means that no improvement is achieved. In the optimization process, the results converge over time and the answers are gradually optimized. The optimization is that initially values are randomly selected and 10% of the optimal answers are passed on to the next generation and the parameters are selected randomly according to the optimal values. The process and range of input values and the type of objective functions are shown in Table 3.

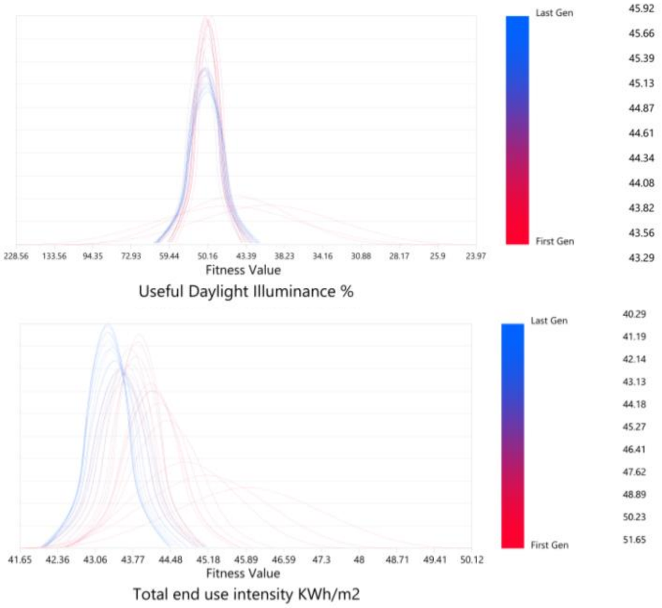

Fig. 10. Standard deviation of objective functions

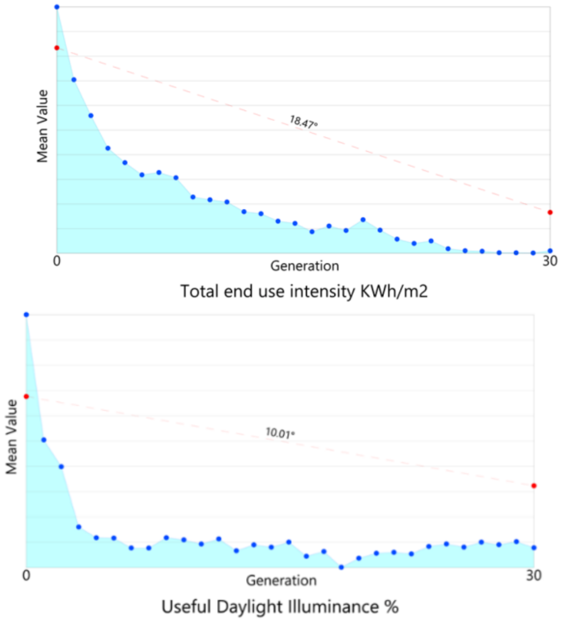

Fig. 11. Data average trend line chart

Table 3. Input and output parameters

	Variable parameters			Change interval
Input	Window to wall area	Northeast Class Northwest Class Southwest Administrative Front	Southeast Class Northeast Office	14 modes with 0.05 intervals From 0.1 to 0.8
	Integrity and non-integration of windows			0-1
	Depth of window canopy	Northeast Class Northeast Class	Southeast Class Office spaces	7 modes with 0.05 intervals From 0 to 0.5
Output	Useful daylight brightness (%)			Energy consumption intensity (KWh / m2)

Table 4. Optimal input and output parameters

Subdivide	North-CN	East-CEW	West-CEW	North-ONS	South-ONS	Shade-CN	Shade-CEW	Shade-ONS	UDI%	EUI (KWh/M^2)
1	0.4	0.25	0.25	0.6	0.3	0.5	0.1	0.4	54.59	44.12
1	0.3	0.25	0.25	0.65	0.3	0	0	0.1	54.36	44.01
1	0.25	0.25	0.25	0.6	0.25	0	0.1	0.4	54.22	43.85
1	0.2	0.25	0.25	0.4	0.3	0	0	0.1	53.18	43.43
1	0.2	0.25	0.2	0.3	0.25	0	0	0.1	51.66	43.10
1	0.2	0.25	0.2	0.3	0.25	0	0	0.1	51.66	43.10
1	0.2	0.25	0.2	0.3	0.25	0.2	0	0.1	51.05	43.09
1	0.15	0.25	0.15	0.3	0.4	0	0.2	0.1	48.40	43.32
1	0.2	0.2	0.2	0.15	0.2	0	0	0.1	44.72	42.91
1	0.2	0.25	0.15	0.15	0.2	0	0	0	43.82	42.85

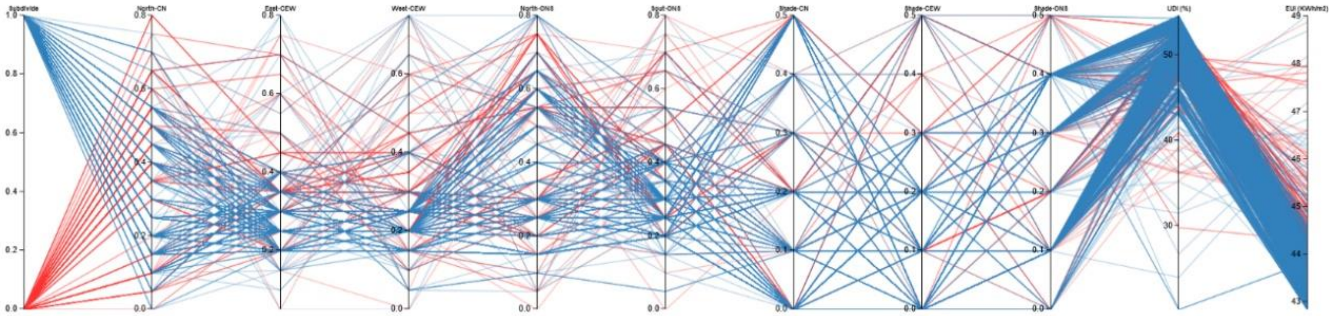

Fig. 12. Parallel Coordinate Chart

In addition, the parallel coordinate diagram of all simulation responses is shown in Figure 12. In this diagram, the rest of the inputs can be checked by restricting one input. Therefore, according to the achieved options, the research objectives can be checked as a single objective, after the optimization completed.

Finally, the goal is to achieve the optimal option in terms of research objectives in which the energy consumption intensity is 43-43 kWh per square meter and determined about 53% of the useful daylight in the total classrooms and office rooms. These numbers have been improved respectively, by 12% for energy consumption intensity and 38% for daylight efficiency, in compared with the non-optimal state (Table 4).

It should be noted that according to the results of previous simulations from the point of view of validation, Honeybee and Ladybug add-ons have been validated by several previous researches. Therefore, in this research, these add-ons have been used to perform daylight and energy analysis. One of the important parameters in optimizing daylight brightness is the useful daylight brightness, which is considered in the range of 300 to 2000 lux, so that the lighting in this range is acceptable in accordance with the standards. The height of the work surface from the floor is 80 cm. The percentage of windows can be changed with intervals of 0.05 and starting from 0.1 up to 0.8. Accordingly, the optimal dimensions of the window- to- wall ratio for classrooms that receive southeast light is about 25%, the optimal dimensions of the window-to-wall ratio for classrooms that receive northwest light is about 25%, the optimal window-to-wall ratio dimensions for classrooms that receive northeast light is about 20%, the optimal window-to-wall ratio dimensions for office rooms that receive southwest light is about 30%, the optimal window-to-wall ratio dimensions for office rooms that receive southeast light is about 40%, The depth of the canopy is 0 cm for all classrooms and office spaces and 10 cm for horizontal windows for the northeast side of the office space. In the following, the useful brightness analysis of the optimal ground floor plan is shown. It is clear that in all spaces other than communication and other uncontrolled spaces, that have not been seen in the light analysis process, the required light is provided in most places and times of the year.

One of the important parameters in optimizing daylight illumination, as previously mentioned, is the beneficial daylight illuminance, which is considered to be in the range of 300 to 2000 lux, ensuring that illumination within this range is acceptable according to standards. The work plane height from the floor is considered to be 80 centimeters. The window percentage changes in intervals of 0.05, starting from 0.1 and up to 0.8. Accordingly, the optimal window-to-wall ratio dimensions for classrooms receiving southeast light is around 25%, for classrooms receiving northwest light is around 25%, for classrooms receiving northeast light is around 20%, for office rooms receiving southwest light is around 30%, and for office rooms receiving northwest light is around 40%. The shading depth is 0 for all classrooms and office rooms, while for the northeast side windows of the office rooms, a horizontal shade of 10 centimeters is anticipated.

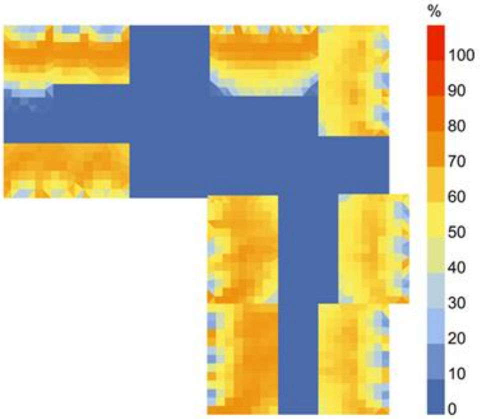

Fig. 13. Useful daylight brightness of the ground floor plan, optimal simulation option

Following that, the beneficial daylight illuminance analysis of the optimized ground floor plan is shown. As illustrated, the overall spaces, excluding the communication and uncontrolled spaces not considered in the lighting analysis, meet the required light in most areas and times of the year.

The results have shown that building energy consumption improved by about 12%, and beneficial daylight illuminance improved by approximately 38% after optimization. This pre-construction improvement can be very significant and effective. The final building details after optimization were presented in the previous chapter, but generally, the optimal window-to-wall ratio dimensions for classrooms receiving southeast light is around 25%, for classrooms receiving northwest light is around 25%, for classrooms receiving northeast light is around 20%, for office rooms receiving southwest light is around 30%, and for office rooms receiving southwest light is around 40%. The shading depth is 0 for all classrooms and office rooms, while for the northeast side windows of the office rooms, a horizontal shade of 10 centimeters is anticipated.

Finally, the final design is based on the studies, simulation results, and standards mentioned in publication 697, with the documentation provided.

One of the limitations of this study was that there are many effective parameters impacting the optimization of the window-to-wall ratio, some of the most important of which include ventilation, heat, view-related issues, lighting, and so on. In this study, only two parameters—lighting and energy—were specified as the research objectives, while other goals were omitted. Another limitation of this study was the lack of access to powerful cloud systems. As a result, by modeling international research articles, a part of the building was used as a benchmark for evaluating the entire building to analyze both mentioned objectives.

The methodology and findings of this study can be extended to other building types and climates by adapting the optimization parameters to fit different conditions. For instance, in different building types such as residential, commercial, or industrial, specific parameters like occupancy patterns, internal heat gains, and usage types would be considered. These variations would allow for a more tailored optimization process that aligns with the specific requirements of each building type.

Additionally, extending this study to different climates would involve adjusting climate-specific parameters such as solar radiation, temperature ranges, and humidity levels. This could be achieved by using regional climate data to simulate various environmental conditions and determine the optimal window-to-wall ratios and shading solutions for different climatic zones.

By modifying the input parameters and optimization criteria accordingly, the approach used in this study can provide valuable insights and practical solutions for enhancing energy efficiency and daylight performance across a diverse range of building types and climates.

5. Conclusions

The results showed that after optimization, the energy consumption of the building improved by about 12%, and the useful brightness of daylight improved by about 38%. The optimal window-to-wall ratio for different spaces was concluded as follows:

- Classrooms receiving southeast light: ~25%
- Classrooms receiving northwest light: ~25%
- Classrooms receiving northeast light: ~20%
- Office rooms receiving southwest light: ~30%
- Office rooms receiving southwest light: ~40%

The depth of canopy for all classrooms and office spaces was 0 and 10 cm horizontal canopies are considered for northeast windows of the office spaces.

The findings of our study underscore the critical importance of considering building orientation when optimizing window design. Different orientations receive varying amounts of natural light and thermal energy throughout the day, which significantly impacts both energy consumption and daylight performance.

By tailoring the window-to-wall ratio (WWR) and shading devices according to specific orientations, we can maximize daylight utilization and enhance energy efficiency. For example:

- **Southeast and Northwest Light**: Classrooms optimized with a WWR of ~25% for these orientations showed substantial improvements in daylight performance.
- **Northeast Light**: A WWR of ~20% was found to be optimal for classrooms receiving this orientation.
- **Southwest Light**: Office rooms with WWRs of ~30% and ~40% demonstrated optimal energy and daylight performance.

This approach not only ensures adequate natural lighting and reduced energy consumption but also enhances occupant comfort by balancing visual and thermal conditions.

Although the results of the article show the optimal window dimensions for improving daylight and energy consumption of educational buildings in hot and dry climates, for this purpose, data from the city of Yazd was used; however, by comparing the data with other cities in hot and dry climates and generalizing the results to other cities, data and information can be analyzed.

While our study focused on optimizing the window-to-wall ratio (WWR) and shading devices for enhancing energy efficiency and daylight performance, there are additional design parameters worth exploring in future research. We recommend the following directions for further study:

Glazing Type: Investigate the impact of different glazing types, such as low-emissivity (Low-E) coatings, triple glazing, and electrochromic glazing, on both energy consumption and daylight performance.

Shading Devices: Evaluate the effectiveness of various shading devices, including external blinds, internal shades, and dynamic shading systems, in different climatic conditions and orientations.

Thermal and Visual Comfort: Incorporate parameters related to thermal and visual comfort to develop a more holistic approach to building performance optimization.

Climate Zones: Extend the study to other climate zones, considering regional variations in solar radiation, temperature, and humidity levels to determine the optimal design solutions for diverse environments.

Building Types: Apply the methodology to different building types, such as residential, commercial, and industrial buildings, to assess the generalizability of the findings and provide tailored recommendations for each category.

By exploring these additional factors, future research can provide a more comprehensive understanding of how to optimize building design for energy efficiency and occupant well-being.

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