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Integrating Thermal and Lighting Analysis to Optimize Window Size of Educational Buildings

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Abstract

Designing buildings with the lowest possible cost base is an essentiality in sustainable architecture. Previously, due to the computational complexity of building's energy consumption, the environmental impact on thermal and lighting energy consumptions haven't been considered simultaneously. As non-linear relationships are often disclosed, a comprehensive approach is necessary to reduce the total energy need of a building and optimize the façade configuration at the same time. Solar radiation affects thermal and lighting energy consumption which depends on building fabric’s characteristics. In this paper a parametric method to optimize the window size and sunshade dimensions of an educational building in mild climate of Iran is presented. Through integrating thermal and lighting energy consumption, 6750 window and sunshade configurations are studied and compared. First, climatic parameters and thermal analysis are validated by on-site measurements. Then, the characteristics of the simulated model and all thermal and lighting parameters have been defined. Finally, the best solution is optimized through genetic algorithm. The results show that, in the first phases of the design process building’s characteristics should comply with national code regulations and then components of the building will be optimized. Additionally the horizontal windows with higher sill levels are more energy-efficient in classrooms.

Keywords:Optimizing, window size, energy consumption, Lighting, Thermal.

1. Introduction.

Utilizing natural free energies in buildings will decrease energy consumption, air pollution and the

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greenhouse effect. Solar energy, the most important renewable resource, affects thermal and lighting energy consumption of buildings with regards to their constructional characteristics.

Electrical energy used for artificial lighting in a building has a good potential for energy saving. However, the use of day lighting should be regulated to avoid high illumination levels, which may cause visual discomfort, overheating problems and an increase in cooling loads of the building [1-2]. In addition, natural gas is one of the products predominantly used for heating and maintaining thermal comfort inside buildings in Iran. Thus, energy consumption to a large extent is related to the heating and cooling demand as well as the lighting demand [3].The discrepancy between window's effect on thermal and lighting energy consumption is one of the research topics nowadays. The configuration of the façade can affect three terms of the annual energy demand of a building, as defined in EN 15603 [4]: the energy need for heating (EH), the energy need for cooling and dehumidification (EC), the energy need for lighting (EL). “The other three terms of the total energy demand of the building – i.e.; energy need for ventilation and humidification, hot water and other services are not directly affected by the configuration of the façade” [5]. “Through well-designed and regularly cleaned skylights, windows, doors, and glass-block wall areas, useful quantities of daylight may be provided in buildings [6]”. Choosing window features is a key step on building design [7]. Thermal and daylight performances are affected by many correlative factors such as glazing size and characteristics, shading properties and its control system, room aspect ratio and its orientation [8]. In spite of the numerous studies on energy efficiency in buildings in the last decades, most of the new constructions are not being designed properly with regard to the integration of daylight with electric lighting and HVAC systems [9]. According to the advancement of computing and programming technology, analyzing and optimizing the architectural concept due to saving energy parameters is considered as a major step in the sustainable design process. Also it helps scientists to analyze these obscure subjects.

The purpose of this paper is to determine the approximate window width to height ratio (WHR), window position and its sunshade size on building’s façade that would provide the minimum energy consumption by integrating artificial lighting and air-conditioning analysis, whilst maintaining internal comfort conditions by a parametric approach, in which 6750 window configurations with different WHR and window placements of an educational building in the mild climate of Iran are analyzed.

2. Literature review

Energy conservation is an important factor in contemporary sustainable building design. The impact of WWR on daylighting and thermal performances of a building have been investigated since 1977 [5, 10].Fransisco in 1977 studied the influence of WWR and the algorithm of sky luminance on lighting, cooling and heating energy consumption which results in 50% saving energy in Texas. He applied a mathematical and comparing method to optimize the area of the window which depends on the feature of the sky algorithm of illumination [10]. Also there is a report to Australian Building Codes Board on optimal Window Size for energy efficiency, Peter and associates in 2008 used Designbuilder and EnergyPlus software for modeling. They simulated an office building and compared its cooling, heating and lighting energy consumption of four deferent WWR (0-10-20-40 %), also they used their model to compare the total energy consumption of a single clear glass and a double clear glass in three different latitudes in Australia. They showed that, the optimal window size by considering the sum of the cooling and lighting energy as a function of WWR (0-10-20-40%) is when the WWR is equal to 10% in all climates [11]. Hassouneh et al. present influence of windows on the thermal energy balance of apartment buildings in Amman. They use self-developed simulation software (SDS) for their analysis, and studied seven types of window glasses, four main orientations, and 10 different percentages for WWR has been considered. However, the effect of solar radiation on lighting energy consumption is not mentioned [12]. Goia et al. present a methodology to consider the optimal transparent percentage in a façade module for

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low energy office buildings. They studied the impact of the window-height on total energy consumption [5].

The impact of window size on ventilation and view comfort has also been investigated. Stavrakakis et al. using CFD analysis, presented a novel computational method to optimize window sizes for thermal comfort and indoor air quality in naturally ventilated buildings [13].Also, Ochoa et al. determine the suitability of combined optimization criteria on window sizing procedures for low energy consumption with high visual comfort and performance. They used EnergyPlus for their analysis and WWR parameter is employed to compare different window-sizes [14], but the impact of the length to width ratio of the window, isn't mentioned. In addition a smart -window's system influence on reducing energy consumption has been considered in Dussaul et al [15].

Other researches study the impact of the building materials especially in zero energy houses on lighting and thermal energy consumptions. Mari et al. showed that in a passive house with insulated envelope and triple-glazed window in Gothenburg, the size of the energy efficient windows does not have a major influence on the heating demand in winter, but is practical for the cooling need in summer by increasing ventilation, and reducing the lighting energy consumption. Finally it mentions that the WFR (window area to floor area ratio) should not be less than 10%. It should be noted that, the result of the paper is for a passive house which has a thermal-break cover [16].

The impact of the shading devices on building thermal and lighting energy consumptions has been investigated recently. E.S. Lee et al. through a one year experiment revealed the impact of automated venetian blind and lighting system performance on total energy consumption in a full scale office building. They found that 45degree blinds reduce daily cooling load by 7-15% and daily lighting energy load by 19 to 52%. 0 degree blind angel reduces 17-32% of daily cooling load and -14 to11% of daily lighting energy load. Also with no daylight controls, daily lighting energy will reduce from 22 to 86%, and cooling loads reduce by 28$\pm$5% in California climate. Finally it presents that for manual operation with fully retracted blinds, lighting savings could be further decreased, but cooling loads would be increased [17].

The methodology of optimizing the window size and related parameters which is used for the objective function is really influential. Grynninga et al. suggested three different rating methods and applied them to assess the energy performance of several window configurations. It has been found that various rating methods give different energy saving potentials in terms of absolute figures [3]. Also Shikder et al. defined a method to optimize window size and its location on a south wall in a patient's room. They used Ecotect and Radiance software for Thermal and Lighting analysis, and DF method, but detail electricity consumption for artificial lighting has not been considered in the study [18].

As seen in the literature, there are two main phases of energy analyzing in buildings: thermal analyses of windows and lighting analyses. The former research developed the separate and independent energy analyses models to optimize window size. Simulating techniques have been noticeably utilized for solving this type of problems so far. It should be noted that the energy consumption of the building is affected by thermal and lighting analyses simultaneously. In addition, the focus of reviewed articles is on office buildings, while educational buildings should be energy efficient, too. We developed an integrated thermal and daylight analyses to optimize window dimensions and location in educational buildings of a mild and humid climate. Also many researchers have not considered the glare influence on window-to-wall ratio (WWR) optimization, a subject under consideration in this paper.

3. Method

Optimizing Window characteristics in very first steps of the design has no effect on the initial cost of the construction, but will reduce the costs generated during the operation of the building. For this reason a model is prepared to integrate thermal and lighting analysis using a parametric method to optimize window size and position on building's façade and solve the incoherency between thermal and lighting functions by determining the appropriate ratios of window wall (WWR), and width to height (WHR).

In the modeling procedure, first the properties of the simulated space and the adjacent zones, such as their construction characteristics, thermal and lighting controlling systems, shading devices and other related parameters are defined. Then, the analyze period is mentioned and lighting parameters like sensor arrangements, testing mesh, lighting power, ballast loss factor, standby factor, delay time of the lamp are assigned. After that all thermal parameters like infiltration rate, number of people per area, ventilation, equipment load and all lighting and air conditioning schedules are designated. Next, lighting and thermal set points are specified and finally the results are integrated and optimized by genetic algorithm.

The process of modeling is displayed in Figure1. There are four main steps: defining the building characteristics and its requirements, validating weather file data by empirical experiment, determining input parameters for the lighting and thermal analysis and clarifying variable parameters and fitness function for optimization algorithm [19].

The integrated thermal and daylight simulations are carried out using EnergyPlus V8-1-0 [20], Daysim 1.08[21] and Radiance 2.01[22] software performing calculations on hourly basis for an entire year. The integration process is designed byRhinociros5software and its Grasshopper 0.9.0075, Honeybee 0.0.55, Ladybug 0.0.58plugins.

In this paper according to national building codes No. 19 and 13, an educational building in mild climate of Iran is audited and its characteristics are modified. Then by a parametric method of integrating thermal and lighting energy consumption, its window size and sunshade dimensions are optimized through evaluating 6750 window and sunshade configurations.

3.1. Evaluating lighting quality

The metric used to evaluate the daylight provision was the "useful daylight illuminance" (UDI) scheme. "UDI is defined as the annual occurrence of illuminances across the work plane where all the illuminances are within the range of 100-2000 lux. Illuminances exceed the upper limit is indicative of the potential for occupant discomfort" [23].

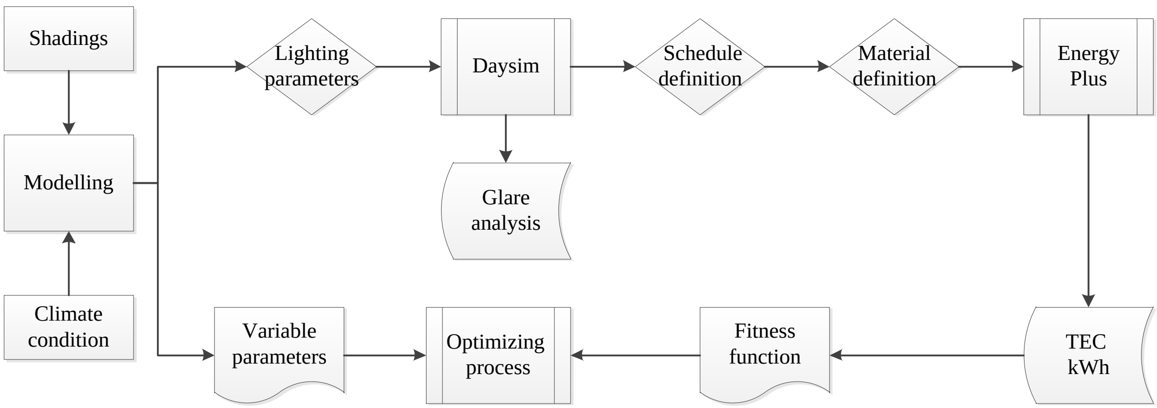

Fig 1: Modelling process

3.2. Optimizing criteria for decision making

In order to integrate optimization process of window size with lighting and thermal energy analysis, genetic algorithm, which is an evolutionary type of algorithm, has been selected. It is noteworthy that

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Evolutionary Algorithms don't guarantee an exact solution, however newer answers generally have a higher quality than older ones. For this algorithm a fitness function and some variable parameters is needed. The fitness function is defined as follows (Eq 1).

$$TEC = \sum E_C + \sum E_H + \sum E_L \qquad (1)$$

Where (TEC) the Total Energy consumption of a building, Cooling energy consumption (Ec), Heating energy consumption (Eh), and Lighting energy consumption (EL) are in kWh.

TEC is the fitness function which should be minimized for optimization process. Furthermore variable and constant parameters for simulation process are defined as follows:

Window height and width, sill and lintel level are variable parameters. As a result WWR, WHR will be optimized. The constant parameters are: the number of zones which are analyzed, building's occupancy program, window pane specifications, that is U factor value (Thermal conductance) and SHGC (Solar Heat Gain Coefficient).Specifications of the building elements of the studied model are: roughness value, thickness, conductivity and density, specific heat, thermal absorption, solar absorption, visible absorption, effective mass of partitions, heating and cooling set point temperatures, and HVAC system.

3.3. Model characteristics

First we define characteristics of the model under study. It is a classroom of an educational building (Fig 2) in the mild climatic zone of Iran. It is situated on the second floor and has one external wall. Other building elements are considered to be internal mass and adiabatic. The room has a single skin facade and is7.16m (width) x 5.2 m (depth) x 2.8 m (height).

The window area limits are displayed in Figure 3. The Window is placed in the center of the south wall. The minimum sill level is assumed to be 0.8m, due to the standard height of a working plane. Also the maximum lintel level is 2.4m.Maximum window width is 6.56 m. The center of the window is one of the variable parameters shown in Figure3.

Fig 2: 22ndBahman secondary school in Rasht

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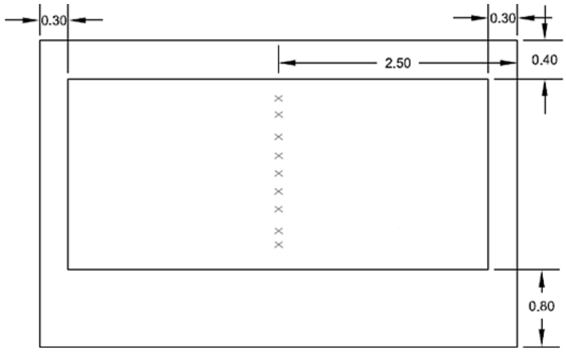

Fig 3: The window area limits

According to Figure2, there are many different configurations for window sizes and positions. Therefore, the range of the parameters should be restricted. Window height is increased at 0.4m intervals, with six different values. Window width is increased at 0.44 m intervals. It has eleven different values. In addition 9 points at 0.2m intervals are selected for the center of the window and Window sunshade dimensions are increased at 0.1m intervals. It also has fifteen different values. Therefore 6750 configurations are compared for optimization procedure. The main orientation of buildings in Rasht is due south. The optimal orientation simulated by Weathertool software is also south.

The Specifications of the building components are those which are recommended for 4A climate zone in ASHRAE [24], and Iranian National Building Code No. 19 [25]. PVC double glazed window with total U value of 2.9 W/m2K is selected. The U values of building components are listed inTable1. The RGB reflectance for the walls, window, floor and roof is 0.5, 0.654, 0.2, and 0.35 respectively.

Table 1: U values of the building components [25]

	Window	Internal walls	Floor	Roof	External wall
U values(W/m^2K)	2.9	2.5-adiabatic	1.4	0.6	1

Furthermore Internal loads which are dependent on the number of people per area, lighting density, infiltration rate per area, ventilation rate per person, equipment load per unit area are shown in Table2.

Table 2: Internal loads

Ventilation rate (CFM/ person)	Infiltration rate perunit area (%)	number of people per unit area(people/m^2)	lighting density (W/m^2)	equipment load (W/m^2)
7.5	0.0005	0.6	2.2	0

An ideal HVAC system is considered in the design, with heating set point of 20oC, and cooling set point of 25oC,also lighting set point is 135 lux [26].

Electrical lighting usage was predicted on the basis of typical schedules and daylight availability using the auto dimming and occupancy scenarios. In Figure 4 the arrangement of daylight sensors over a working plane with 0.8 meters height is displayed.

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4. Field measurements and validations

Here, comparisons between the 5-year average temperatures and the simulated weather data, between the measured daylight illuminance and those simulated, and comparison of monthly thermal energy consumption in 2011 between the heating gas bills and the results of the simulated data are presented.

4.1. Weather data validation

To define an accurate and complete weather data for the simulated model, the EPW (EnergyPlus Weather file) file obtained from Meteonorm software is compared with 5-Year meteorological data from Rasht meteorological organization. A luxmeter logger LX-1128SD (0-100000 Lux, ± (4 %+2 dgt)) (Fig5), placed on the 7th floor of an apartment building on 8th August 2015 was used for lighting measurements.

In Figure 6 the comparison between the 5-year average monthly temperatures and the simulated data is displayed. As shown, the correlation coefficient is 0.99, and the difference between the two sets of data is equal to 4.7%. In addition in Figure 7, the comparison between the measured daylight illuminance and those simulated is presented. The correlation coefficient is 0.99, and the difference is equal to 3.7%.This presumably relates to the differences of the sky cloud coefficients.

4.2. Thermal energy consumption

Before doing any analysis, it is necessary to validate the simulation process. In Figure 8 the comparison of monthly thermal energy consumption in 2011, between heating gas bills and the results of the simulated data is displayed. The correlation coefficient is 0.97, and the simulation error is equal to 2.8% which is negligible.

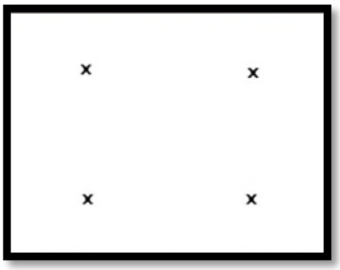

Fig 4: Arrangement of daylight sensors in the classroom

Fig 5: Luxmeter logger (LX-1128SD)

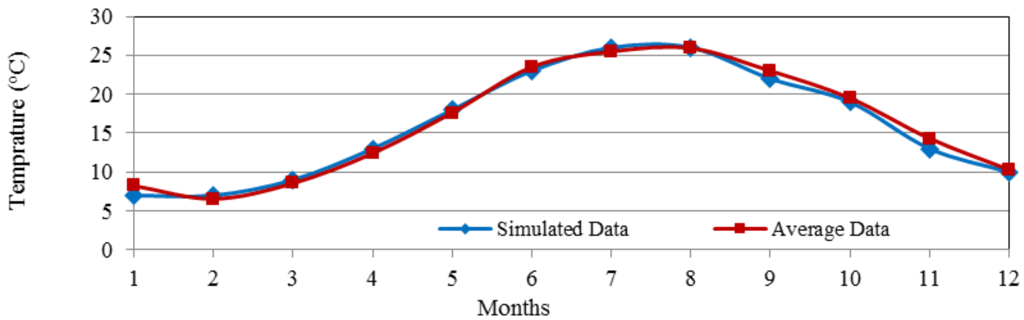

Fig6: Comparison between monthly average temperature data used in the simulation and averages of 5-Year meteorological data

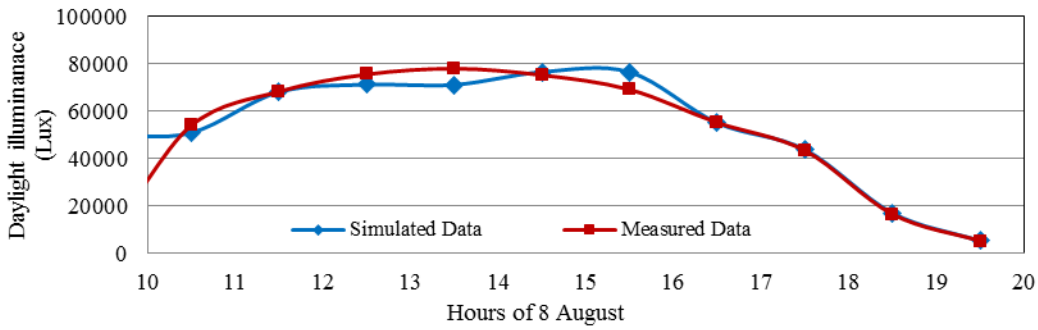

Fig 7: Comparison of daylight illuminance values on 8th August between the measured and the simulated data

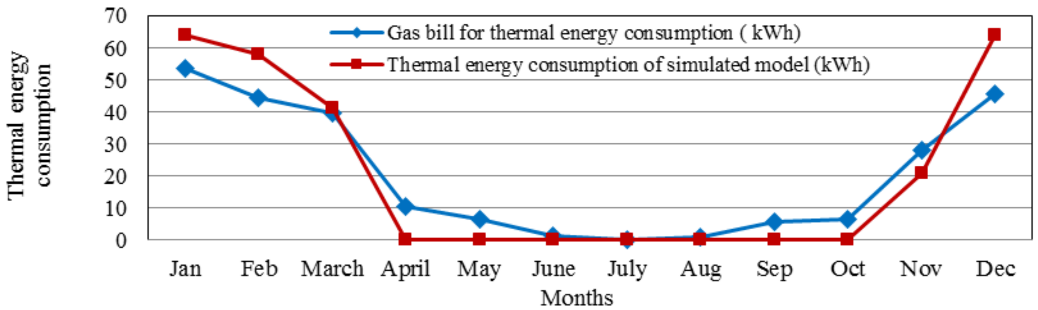

Fig 8: Comparison of monthly thermal energy consumption in 2011 between the gas bills and the simulated data

5. Results

In the following, the TEC of heating, cooling and lighting of the classroom, with the optimal window and shading devices, analyzing 6750 configurations and its audited situation is compared.

5.1. Classroom audit

The current building does not conform to the National Building Code No. 19 [25]. In addition, comfort conditions are rarely provided throughout the year (Figure 6). Therefore, regarding Code No. 19 [25] some strategies should be undertaken to improve thermal and lighting conditions and reduce the cost of the electricity and gas bills by decreasing the energy use.

There are two fluorescent lamps in the classroom, which according to the high school occupancy schedule, consume 176kWhelectricity energies in a year. There isn’t any daylight control system in the classroom.

5.1.1. Auditing classrooms lighting

According to the lighting schedule of the classroom, the lighting simulation by Dialux software shows that the illumination intensity of the classroom under study is less than 150 lux (Fig 10- Right). Regarding National Code No. 13 [26] the appropriate illumination intensity in a classroom should be 200-500 lux. Therefore, the number of lamps is increased, and both the lighting quality and quantity are improved (Fig 10- Left). The result is the increase of lighting power to 425 W.

5.1.2. Auditing classrooms components and its lighting system

To improve the building’s energy consumption, the following measures according to Code No. 19 were undertaken: controlling the infiltration and ventilation, using thermal insulations in the building's external envelope, using double glazed PVC window and providing daylight control system (Auto dimming system, always on during occupancy hours).As a result, the energy consumption of the classroom reduced from 31.38 kWh/m2 (1255.2 kWh per year for the classroom) to 10.9 kWh/m2 (430.4 kWh per year for the classroom) or 65% per year. In Table 3 the annual heating, lighting and cooling energy consumptions of the classroom are presented.

In this situation two classroom windows with 2m width and 1.5m height have been unified as one window with 4 m width, 1.5m height and 0.8m window sill level. (Fig 11)

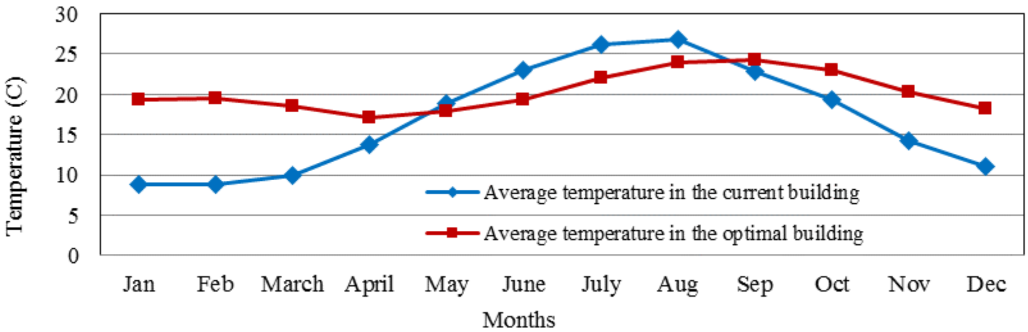

Fig9: Comparison of internal monthly temperature of the current building and the optimal one

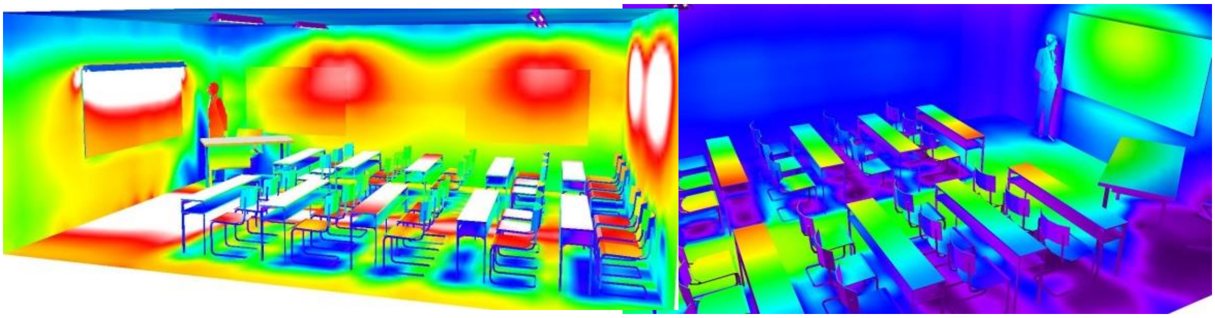

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Fig10: Illumination intensity in the classroom. Right: current building. Left: optimal building

Fig11: window of the classroom

Table 3: The annual heating, lighting and cooling energy consumption of the optimal classroom

Lighting (kWh)	**Cooling**(kWh)	**Heating**(kWh)	**TEC** (kWh)
142.6	103	184.9	430.4

5.2. Optimizing window size using genetic algorithm

In order to integrate optimization process of window size with thermal and lighting energy analysis, genetic algorithm, which is an evolutionary type of algorithm, is selected.This process, is used by Galapagos plugin of Grasshopper in Rhinoceros software. Window height and width, window's center, its sill and lintel level are defined as the variable parameters or genomes. Also, the value of the algorithm population and stagnant is considered constant and equal to 10, which means after finding the optimal solutions, optimization process will be continued with 10 other populations to certify the answer. In Figure 12 the optimizing process is displayed. As shown, the optimal TEC is 406.5 kWh by calculating 160 of 6750 modes. So by comparing the optimal result with those of audited in section 6.1, it is revealed that the optimization of the window size and its shading device can reduce the annual energy consumption by 6%. The optimal window has 0.96 m height, 3.9 m width and is located at 1.32 m above the finished floor. It also has horizontal shading with 0.4 m depth (Fig 13).

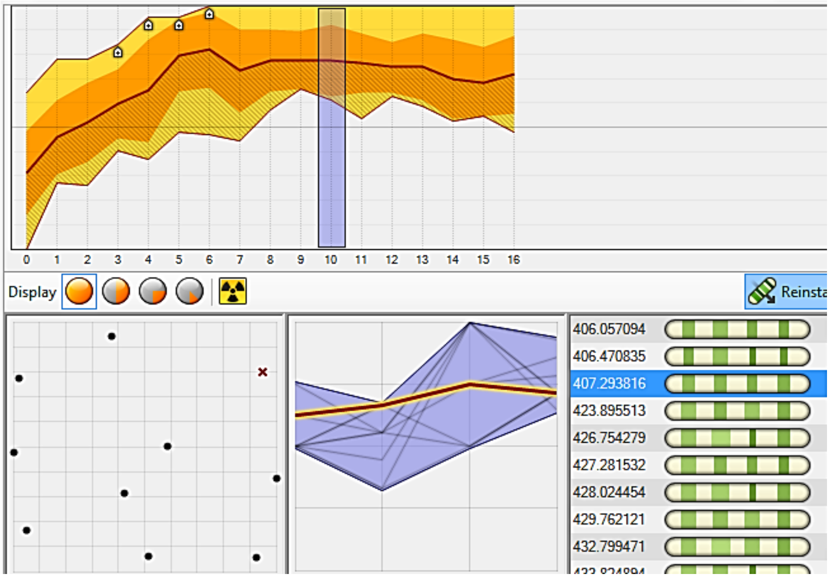

Fig 12: Optimization process of size and position of the south window, and its shading by Galapagus plugin

Fig13: the optimal window of the classroom

In Table 4, the dimensions and positions of the fifteen optimal windows and shading devices are presented. As shown, horizontal windows with high sill levels are more appropriate. The average width to height ratio (WHR) of these windows with the minimum TEC is 1/4 m. The optimal windows have 0.2-0.6 m width sunshades. As seen the eighth optimal window has the maximum WWR (window wall ratio) (Fig.14).

Table 4:Fifteen optimal results obtained for the window and sunshade dimensions and positions

No.	**Sunshade Width (m)**	**Window width (m)**	**Window High (m)**	**Window sill level (m)**	**Heating (kWh)**	**Cooling (kWh)**	**Lighting (kWh)**	**TEC/m² (kWh/m²)**	**TEC (kWh)**
1	0.4	3.9	0.96	1.32	168.7	79.8	157.5	10.3	406.05
2	0.2	3.9	0.8	1.6	159.8	82.3	164.2	10.3	406.4
3	0.5	4.6	0.96	1.32	177.7	78.2	151.3	10.34	407.2
4	0.4	5.2	0.64	1.68	170.8	71.6	166.9	10.39	409.4
5	0.3	4.6	0.64	1.68	162.8	75	171.5	10.4	409.46
6	0.4	4.6	0.96	1.32	174.2	83.3	152.5	10.4	409.9
7	0.4	4.6	0.8	1.6	170.1	76.7	163.2	10.4	410.1
8	0.5	4.6	1.2	1.2	184.2	89	137	10.4	410.3
9	0.2	3.9	1.2	1.2	169	98.1	143.7	10.4	411

10	0.2	4.6	0.64	1.68	159.4	79.6	172.4	10.4	411.5
11	0.6	3.9	1.2	1.2	179	80.9	151.9	10.4	411.9
12	0.4	3.2	0.96	1.32	162.5	77.5	172.3	10.4	412.4
13	0.3	3.2	0.96	1.32	160.2	80.8	171.5	10.47	412.6
14	0.5	3.9	1.2	1.2	176.2	85	151.5	10.48	412.7
15	0.4	4.6	0.64	1.68	165.7	71.3	177.2	10.5	4

In Figure 15 the distribution rates of above 150 lux of daylight illuminance on a 0.8m height working plane during the year for the first and eighth optimal windows (Table 4) are compared. The optimal window provides 52% of the interior lighting demand throughout 60% of the classroom. But the eighth optimal one, (the largest), provides 60 % lighting demand for 70% of the classroom. Then by optimizing window size and its position on the wall, the lighting penetration depth can be controlled. Figure 16 displays the glare rate that is the distribution of above 2000 lux of solar radiation over the working plane. As it can be seen, the first optimal window provides lighting comfort throughout the living room except for 45% of the day and near the window. But the eighth optimal window is not a good solutions it doesn’t satisfy the comfort limit.

Fig14: The eighth optimal (the largest) window of the classroom

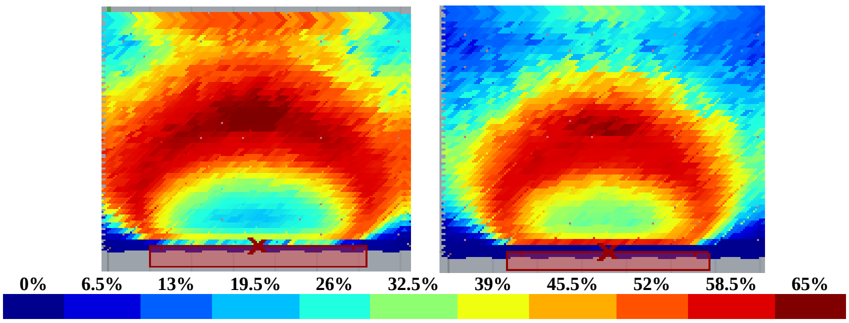

Fig 15: Distribution rate of above 100 lux daylight illuminanceon the working plane during the year. Right: The first optimal window with minimum TEC, Left: The eighth optimal window, (The largest one)

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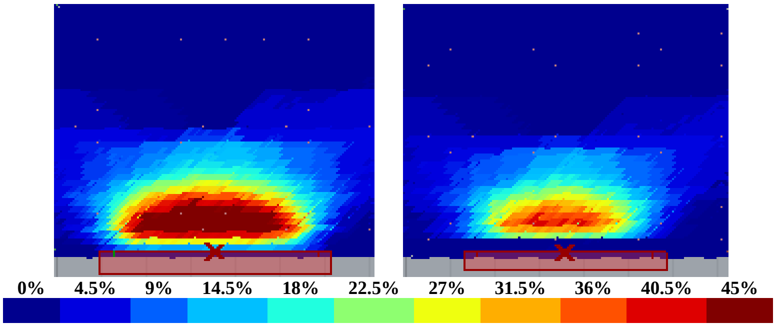

Fig 16: Distribution rate of more than 2000 lux daylight illuminanceon the working plane during the year. Right: The first optimalwindow with minimum TEC, Left: The eighth optimal window, (The largest one)

6. Conclusion

The purpose of this paper is to determine the approximate window width to its height ratio (WHR), window position and its sunshade dimensions that would minimize the energy consumption of the building by integrating artificial lighting and air-conditioning analysis, whilst maintaining internal comfort conditions through a parametric approach. The proposed methodology presents an integrated EnergyPlus and Daysim analysis with optimizing genetic algorithm approach in order to optimize building's window design to achieve thermal comfort and indoor daylight quality.

The results show that, according to the National Building Code No. 19, the auditing strategies such as; controlling infiltration and ventilation, using insulations in building envelope, using double glazed PVC window, providing daylight control system (Auto dimming system during active occupancy hours), reduce the annual energy consumption by 65% without changing the window size. In addition optimizing window and its shading device dimensions reduces the annual energy consumption by only 6%.The optimal sssolutions are the horizontal windows with higher sill level on south wall. Through these measures, day-lighting conditions will also be satisfactory. Therefore, these strategies are a good starting point in preliminary design phase for south oriented window. Thus during the design process, first the project should comply with national codes, and next the building components could be optimized.

The results obtained from the proposed method in an educational building located in mild climate of Iran are applicable to this climate only. In the future, the method can be implemented in other locations in order to highlight the influence of each climate on the optimal WWR of windows for low-energy buildings in different climates. In addition, ventilation and view comfort parameters can be added in to the parametric model process to optimize WWR by integrating all 4 main parameters; lighting, thermal, ventilation and view comfort.

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