Energy Equip. Sys. / Vol. 9/No. 1/March 2021/ 1-12

Energy Equipment and Systems

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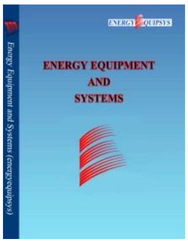

Simulation-based optimization of smart windows performance using coupled EnergyPlus - NSGA-II - ANP method

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Article history:

Received : 4 May 2020
Accepted : 3 June 2020

ABSTRACT

Windows are one of the most important parts of buildings responsible for wasting energy. In recent years, research works have shown that using smart windows is one of the most efficient methods to reduce the negative effects of glazings on buildings' energy consumption. In this paper, the performance of smart windows, including three types of electrochromic and five types of thermochromic ones, on reducing buildings energy consumption has been studied in four major climate regions of Iran (i.e., continental with dry summer, temperate with dry summer, steppe arid, and desert arid). Besides, to optimize the design parameters, including the building orientation, the window dimensions, and the glazing specifications, single and multi-objective genetic algorithms have been applied. The algorithms, coded in MATLAB, have been coupled with EnergyPlus building energy simulation program through jEPlus software as an interface. The results show that in the optimized case, using thermochromic and electrochromic windows decreases the annual total energy consumption 29.6% to 44.7%, and 9.3 to 26.3%, respectively, relative to the base model. The developed method and its results help to build energy engineers and architects to make the most effective decision on building parameters, which improve the energy efficiency of buildings.

Keywords: Building Energy Consumption; Electrochromic Window; Thermochromic Window; EnergyPlus; jEPlus.

1. Introduction

Nowadays, finding effective solutions to optimize buildings' energy consumption is one of the most important aspects of its early design stages. The energy consumed in the building section comprises almost 40% of the whole energy requirement in developed countries [1]. Recent research works have forecasted 6.4% increase in buildings energy consumption in the United States (US) from 2018 to 2050 [2]. Windows are one of the main parts of buildings envelopes responsible for about25% of buildings' energy waste in Iran [3]. So, windows design parameters such as glazing optical specifications [4], dimensions [5], and orientation [6] have paramount importance on buildings' energy performance. As a result,

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simultaneous consideration and optimization of all these factors are vital, which need efficient and robust optimization procedures [7].

Smart windows have a significant impact on adapting buildings' envelopes with the environment. These types of windows can intelligently control the transfer of heat and light through glazings, reduce the energy used by building heating, ventilation, and air-conditioning (HVAC) and artificial lighting systems, and improve occupants' thermal comfort [8]. Electrochromic and thermochromic technologies are the two main types of chromogenic glazings used in smart windows. These technologies make it possible to control solar irradiation transmitted to conditioned zones by diurnal switching of glazings darkness [9]. Previous studies have proved that using smart windows in building facades benefits from greater efficiency of daylight and better control of heat and light transfer, which can compensate some amount of buildings energy loss. For instance, Mahdavinejad et al. [10] investigated the application of smart windows in tropical regions and found out that all types of smart windows, except the liquid crystal one, work properly.

Thermochromic glazing - as a passive technology for smart windows - includes a glass layer that is coated by semiconductor materials. The semiconductor layer enables the glazing to have different colors, and therefore different transmittance, based on its temperature. As a result, the glazing darkness changes gradually in response to visible solar irradiation [8]. The study on thermochromic windows by Saeli et al. [11] for a typical residential room in a variety of climates showed that they are more effective than double clear glazing ones, especially in warm climates. In another research work, the simultaneous application of thermochromic windows and phase change materials (PCMs) was evaluated by Long and Ye [12] in China, which approved the synergic effect of these technologies. More recently, Allen et al. [13] studied the effect of using thermochromic glazings on energy consumption of a cellular office room in Italy using EnergyPlus. Their model used a daylight control to switch off artificial lights if the illuminance was over 500 lux. Besides, the effect of window inclination angle (0°, 30°, 60°, and 90° to the horizontal) on the results was also evaluated. Based on their findings, the thermochromic window has the potential to save buildings energy consumption by up to 22% more than the double glazing one.

Electrochromic glazing - as an active technology for smart windows - consists of five thin layers, including an outside electrochromic layer, an intermediate electrolyte, and an inside lithium ions layer, which are sandwiched between two conductive transparent layers. Applying a direct current (DC) voltage to the conductive layers, ions move from the lithium-ion layer to the electrochromic one through the electrolyte, which darkens the glazing step by step [14]. Sbar et al. [15] modeled a commercial building with electrochromic windows in three different climates of the United States using eQuest energy simulation software. The lighting system of their model was controllable to use the available daylight. According to their results, using electrochromic glazings reduces carbon emission by up to 35% and 50% for new and renovated buildings, respectively. DeForest et al. [16] studied the effect of near-infrared electrochromic (NEC) windows on buildings' energy consumption and CO_2 emission in various climate regions of the United States. They also compared the performance of NEC glazings with two conventional types of windows. According to their results, using NEC windows in all current US buildings leads to 8 TWh saving in primary energy consumption and 1.56 million tonnes reduction in CO_2 emission per year. In another research work, DeForest et al. [17] performed a similar investigation for dual-band electrochromic (DBEC) windows and concluded that they could reduce buildings' energy demand between 60 to 300 kWh/m^2 of windows.

During recent years, researchers have used various types of software and modeling methods to obtain accurate and desirable results for buildings energy optimization problems. They have shown a vast amount of effort in buildings design modification [18-

20]. Among many available building energy simulation programs, the application of someones - e.g., EnergyPlus [21], GenOpt [22], and eQUEST [15] - is prevailing. For example, Joe et al. [23] found an optimum design for double skin facades considering the window type and the cavity depth using EnergyPlus and GenOpt software. In another research, Holst [24] estimated the optimum physical and thermophysical properties of windows by coupling EnergyPlus and GenOpt. Using a similar method, Rapone and Saro [22] investigated the effect of using shadings on buildings' energy consumption. More recently, Delgarm et al. [25] developed a genetic algorithm optimization code using MATLAB coupled with EnergyPlus through jEPlus to achieve the minimum annual building energy consumption. In another study, they accomplished the multi-objective optimization using the weighted sum method [26]. Their results showed that in the optimized case, the annual lighting energy consumption increases only up to 4.8% in contrast to a remarkable decrease in the annual heating and cooling energy consumptions.

In this investigation, specifications of smart windows are optimized to reduce buildings' annual energy consumption using both single and multi-objective genetic algorithms in different climate regions of Iran. Besides, the Analytic Network Process (ANP) method is used to make the best solution in the multi-objective optimization approach. Three electrochromic and five thermochromic windows are studied, and the decision variables are the building orientation, the window dimensions, and the glazing type.

Nomenclature

$\vec{x}$	decision variables vector
X	feasible decision space
$\vec{F}(\vec{x})$	objective function vector
$\vec{g}(\vec{x})$	inequality constraints vector
$\vec{h}(\vec{x})$	equality constraints vector
k	number of objective functions
n	number of decision variables
A	binary comparison criteria matrix
λ_{max}	the largest numerical eigenvalue
i	number of inequality constraints
j	number of equality constraints
C	feasible criterion space
w	eigenvector (inner priority vector)

2. Materials and Methods

In the current work, the thermal behavior of buildings is simulated using EnergyPlus, developed by the US Department of Energy (DOE) [27]. To implement the simulation-based optimization, EnergyPlus is coupled with the optimization algorithm, which is coded in MATLAB. Also, jEPlus manager tool is used as an interface, as discussed in detail in our previous research work [26].

2.1. Multi-Objective Optimization

Mathematical definition to formulate multi-objective optimization problems are as below [26]:

$$\text{Min} \quad \vec{F}(\vec{x}) = [\, f_1(\vec{x}).\ f_2(\vec{x}). \ldots f_k(\vec{x})]^T, \vec{x} \in \mathbb{R}^n$$

$$\text{Subject to: } \begin{cases} \vec{g}(\vec{x}) \leq 0. \vec{g}(\vec{x}) \in \mathbb{R}^i \\ \vec{h}(\vec{x}) = 0. \vec{h}(\vec{x}) \in \mathbb{R}^j \end{cases} \quad (1)$$

$$C = \{F(\vec{x}) \mid \vec{x} \in X\}$$

where $k \geq 1$ is the number of objective functions, $\vec{x}$ is the feasible decision set and $X \in \mathbb{R}^n$ is a present of n decision variables. $\vec{F}(\vec{x}) \in \mathbb{R}^k$ is the objective function vector in which $f_m(\vec{x}): \mathbb{R}^n \to \mathbb{R}^1$. The number of inequality constraints is shown by i, and $\vec{g}(\vec{x})$ is their vector. Similarly, j and $\vec{h}(\vec{x})$ are, respectively, the number of equality constraints and their vector. Ultimately, C is a present of the criteria spaces.

In this research, the Genetic Algorithm (GA) method is used as an optimization technique. Deb et al. [7] extended GA to multi-objective optimization problems by presenting the Non-dominated Sorting Genetic Algorithm (NSGA-II) method. In this case, a curve of optimal solutions is appeared by simultaneously solving the abovementioned system of equations for different objective functions, which is termed as Pareto front. A point belongs to the Pareto front if and only if its value is less than or equivalent to all other points. Thereby, all feasible solutions founded in the Pareto front are the best solutions [28]. To opt for the most desirable solution among all potential ones in a specified circumstance, a decision-making process is needed. In this study, among many available decision-making techniques, the Analytic Network Process (ANP) method is used as it can consider simultaneously both quantitative and qualitative variables as described in detail in the next sections.

2.2. Analytic Network Process (ANP) Decision-Making Method

The Analytic Network Process (ANP) method provides a model to analyze complex multi-objective decision-making problems. It establishes priorities via pairwise comparison and decision, which does not follow hierarchical rules like the Analytic Hierarchy Process (AHP) method [29]. ANP breaks a complex problem down into small pieces to be able to solve them, then merges the results to make the final decision. Besides, ANP lets users understand the interaction among factors in a complex structure. ANP decision-making method includes seven major steps as follow [30]:

1. Establishing the network structure: it defines the decision-making problem, sets up its hierarchy structure, and prioritizes the control criteria;
2. Creating the initial supermatrix: it connects the proper elements to the related decision subnets, either quantitative or qualitative, using the local priority vectors;
3. Making pairwise comparison between the elements of the clusters;
4. Creating the normalized supermatrix: the importance of every element is determined by the eigenvector of the normalized supermatrix;
5. Calculating the limit supermatrix: it is obtained by powering the supermatrix until their elements converge to the same amount in each row;
6. Synthesizing the alternatives from the control criteria level and conducting a sensitivity analysis on the outcomes;
7. Choosing the best result.

3. Case Study

In the present research, a typical south-faced room of a multi-story office building is investigated in Iran, whose specifications have been presented in our previous research work in detail [25]. An isometric view of the base model is presented in Fig. 1, and the thermophysical properties of its envelope in listed in Table 1, which are common in Iran [31]. A 90 W compact fluorescent lamp (CFL) is used as a lighting system, equipped with a daylight sensor to automatically control the artificial lighting with the threshold of 500 lux. The room is conditioned using a packaged terminal heat pump (PTHP) system whose heating and cooling setpoint temperatures are 20°C and 27°C, respectively.

According to Köppen-Geiger climate classification, the climatic conditions of Iran can be categorized into four main regions, including continental with dry summer (Ds), temperate with dry summer (Cs), steppe arid (BS), and desert arid (BW) ones [32]. Tabriz, Tehran, Kerman, and Bandar-e-Abbas are chosen as representative cities for the abovementioned climatic regions, respectively, whose specifications are listed in Table 2 [33].

Table 3 shows the list of decision variables, including the building orientation in the counterclockwise direction, the window dimensions, and the glazing type. Besides, the objective functions include the annual heating, cooling, and lighting energy consumptions without any specific constraint. In NSGA-II method, the population size of 40 individuals, the maximum generation number of 25, the crossover percentage of 70%, the mutation percentage of 40%, the mutation rate of 2%, and the tolerance of 0.001 is used based on preliminary studies to get a trade-off between the time cost and the results reliability.

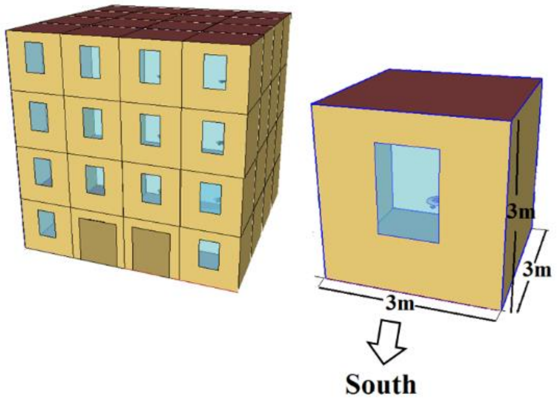


Fig. 1. Isometric view of the base model

Table 1. Thermo-physical properties of the case study envelope [31]

Component	Property	Value
Wall	Conductivity (W/mK)	0.57
	Thickness (m)	0.2
	Specific heat (J/kgK)	790
	Density (kg/m^3)	1120
Floor and Roof	Conductivity (W/mK)	1.11
	Thickness (m)	0.1
	Specific heat (J/kgK)	920
	Density (kg/m^3)	800

Table 2. Climatological specifications of the representative cities [32, 33]

City	Climate Zones	Lat.	Long.	Elev. (m)	HDD	CDD
Tabriz	Continental with dry summer (Ds)	38.08 N	46.28 E	1361	2667	802
Tehran	Temperate with dry summer (Cs)	35.68 N	51.32 E	1191	1588	1540
Kerman	Steppe arid (BS)	30.25 N	56.97 E	1754	1619	1017
Bandar-e-Abbas	Desert arid (BW)	27.22 N	56.37 E	10	71	3220

Table 3. Description of the decision variables

Variable	Unit	Base Value	Range
Building orientation	°	0	continuous [0,360)
Window length	m	1	continuous (0,3)
Window height	m	1.5	continuous (0,3)
Glazing type	-	Clear non-smart	discontinuous Sage® and LBNL® libraries

4. Results and Discussion

As discussed previously, both single-objective and multi-objective approaches are used in this study. In the single-objective optimization method, the annual heating, cooling, lighting, and total energy consumption are separately considered as the objective function. On the other hand, in the case of the multi-objective optimization method, the annual heating, cooling, and lighting energy consumption are used simultaneously as the objective functions.

4.1. Single-Objective Approach

In this section, the base model is optimized at Tehran, located in the temperate climatic region of Iran. As mentioned above, the annual heating, cooling, lighting, and total energy consumption are used as objective functions. The main aim of this part is to understand how different objective function leads to different optimum results in the single-objective optimization approach. Besides, analysis of the optimum optical properties of the window provides us with an idea about appropriate window specifications in other architectural problems.

Tables 4 and 5 summarize the optimum decision variables for the model with an electrochromic and a thermochromic window, respectively. The results include the building orientation, the window dimensions, the window to wall ratio (WWR), and the window type. It should be noted that although WWR is not a decision variable, however, as the gross wall area (the area of the wall including the window) is constant, it can be easily calculated from the window length and height. The window to wall ratio is presented as it is more convenient for physical discussions. Based on the results, in both cases, if the objective function is the annual heating energy consumption, southward orientation is recommended for the building to make it enable to take advantage of sunlight energy.

In contrast, in the case of optimization based on the annual cooling energy consumption, the optimum orientation is almost to the north to protect the building from excessive solar irradiation. Other approaches - e.g., when the annual lighting or total energy consumption is considered as the objective function - lead to an optimum orientation between north and south to balance the pros and cons aspects of solar energy. Besides, according to the results, if the annual heating or lighting energy consumption is used as the objective function, the window dimensions and WWR should be large to exploit the most available sunlight. For the same reason, as the problem is optimized based on the annual cooling energy consumption, the optimum window dimensions and WWR are small to reduce the room solar heat gain.

The objective function also affects the appropriate glazing type. As shown in Table 4, in the optimization of the model with an electrochromic window based on the annual heating energy consumption, 9 mm Blue Sage® glazing is recommended, while in the case of other objective functions, the optimum thermoelectric glazing is 7 mm SR2.0 Sage®. This feature is mainly because of the higher solar transmissivity of Blue Sage® than SR 2.0 Sage® one. As a result, for the annual heating energy consumption minimization, it is preferable to transmit the most solar irradiation to the conditioned zone. This trend is also seen from another point of view in Table 5 for the model with a thermochromic window. According to the results, the optimized case has a 2.24 LNBL® glazing if the objective function is the annual cooling energy consumption. In other situations, the optimum glazing is 1.24 LNBL® due to its higher solar transmissivity than other thermochromic glazings used in the simulations.

According to Figs. 2 and 3, multi-objective optimization based on the annual heating energy consumption reduces the heating energy requirement by 30% and 70% in the case of electrochromic and thermochromic windows, respectively. However, in this situation, the annual total energy consumption increases by 15% and 17% due to the growth of cooling and lighting energy demand. Based on the results, a similar trend can be seen more or less if the annual lighting energy consumption becomes optimized. However, when the annual cooling energy consumption is considered as the objective function, the results are somehow different. In this situation, the cooling energy requirement decreases 49% and 40% for the model with the electrochromic and the thermochromic windows, respectively. Besides, optimization leads to 13% saving in the annual total energy consumption using the thermochromic glazing, while increases the annual total energy consumption 23% if an electrochromic window is used. All of the results support this idea that although single-objective optimization analysis may give some insight into the interaction between decision variables and objective functions, by optimization using a single objective function, variation of other objective functions is not predictable.

Table 4. The optimum decision variables of the model with an electrochromic window in Tehran using the single-objective optimization approach

Decision Variable	Unit	Objective Function			
		Annual Heating Energy Consumption	Annual Cooling Energy Consumption	Annual Lighting Energy Consumption	Annual Total Energy Consumption
Building orientation	°	4.2	179.3	80.0	40.0
Window length	m	2.8	0.5	2.9	1.9
Window height	m	2.8	1.1	2.9	2.5
WWR	-	89.3%	6.4%	93.4%	54.0%
Glazing type	-	Blue Sage®	SR2.0 Sage®	SR2.0 Sage®	SR2.0 Sage®

Table 5. The optimum decision variables of the model with a thermochromic window in Tehran using the single-objective optimization approach

Decision Variable	Unit	Objective Function			
		Annual Heating Energy Consumption	Annual Cooling Energy Consumption	Annual Lighting Energy Consumption	Annual Total Energy Consumption
Building orientation	°	356.0	179.0	38.6	39.0
Window length	m	2.8	0.8	2.9	1.0
Window height	m	2.6	0.8	2.5	1.3
WWR	-	80.6%	7.4%	80.6%	13.8%
Window type	-	1.24 LNBL®	2.24 LNBL®	1.24 LNBL®	1.24 LNBL®

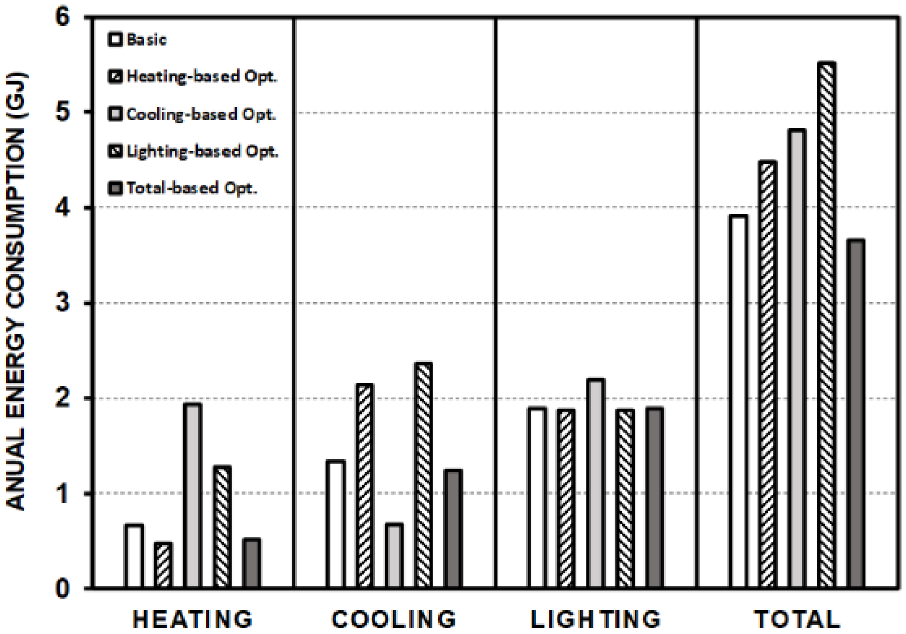


Fig. 2. The optimum building energy consumption for the single-objective optimization of the model using the electrochromic window in Tehran

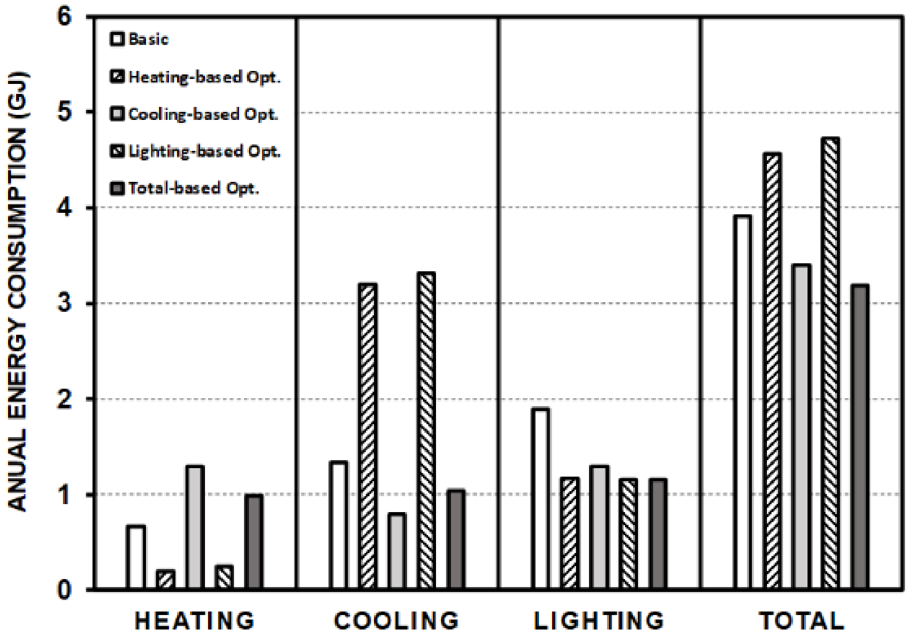
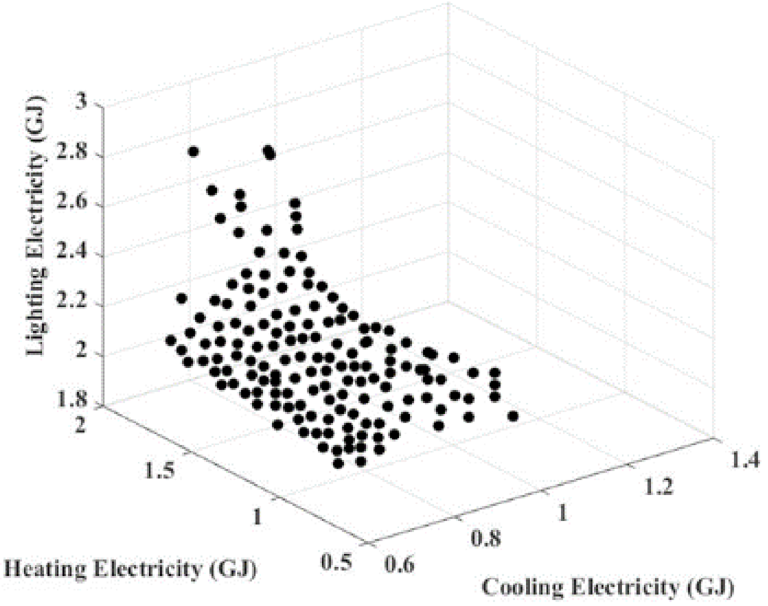


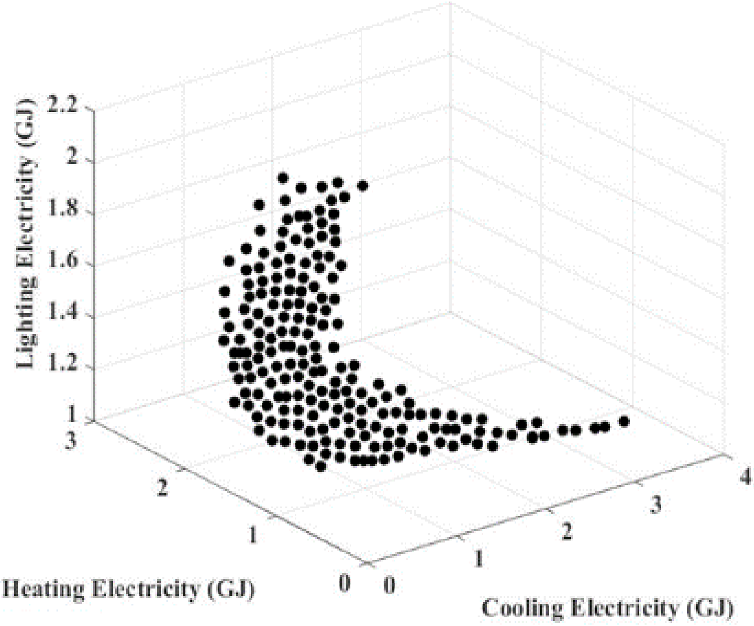
Fig. 3. The optimum building energy consumption for the single-objective optimization of the model using the thermochromic window in Tehran

4.2. Multi-Objective Approach

In this section, the optimization results are presented as the annual heating, cooling, and lighting energy consumptions are considered simultaneously as the objective functions in a multi-objective procedure. Using the NSGA-II method, representative results for the optimum model in Tehran are shown in Fig. 4 as Pareto fronts. As mentioned previously, the final solution among the optimal front is selected using the ANP decision-making method. Tables 6 and 7 summarize the final optimum decision variables in various climatic regions of Iran, in the case of the electrochromic and the thermochromic windows, respectively.



(a)with the electrochromic window



(b) with the thermochromic window

Fig. 4. Pareto front of the multi-objective optimization approach

Table 6. The optimum decision variables of the model with the thermochromic window using the multi-objective optimization approach

Decision Variable	Unit	Tabriz	Tehran	Kerman	Bandar-e-Abbas
Building orientation	°	53.2	39.0	33.9	36.0
Window length	m	2.8	2.8	2.5	1.3
Window height	m	2.9	1.7	1.7	0.7
WWR	-	90.2%	52.9%	47.2%	10.8%
Glazing type	-	SR2.0 Sage®	SR2.0 Sage®	SR2.0 Sage®	Blue Sage®

Table 7. The optimum decision variables of the model with the electrochromic window using the multi-objective optimization approach

Decision Variable	Unit	Tabriz	Tehran	Kerman	Bandar-e-Abbas
Building orientation	°	33.0	32.0	36.0	33.0
Window length	m	2.1	1.0	1.6	0.8
Window height	m	2.8	1.4	1.5	0.7
WWR	-	65.3%	15.5%	27.3%	6.0%
Window type	-	1.24 LNBL	1.24 LNBL	1.24 LNBL	1.24 LNBL

Based on the results, in both cases, the climatic region has no significant effect on the optimum building orientation, so that the southeastern orientation is recommended in all cases. However, its effect on other parameters, especially the window size and WWR, is considerable. As shown in Tables 6 and 7, from the desert arid (Bandar-e-Abbas) to the continental (Tabriz) climate, the optimum size of the window increases to provide the building with more and more solar heat energy. This effect is so that from the desert arid to the continental climate, the optimum WWR grows from 10.8 to 90.2% using the electrochromic glazing and from 6.0 to 65.5% using the thermochromic one. Besides, in all cities, the optimum electrochromic glazing type is 7 mm SR 2.0 Sage®, except in Bandar-e-Abbas in the desert arid climatic region, which needs a 9 mm Blue Sage® one. This feature is mainly due to the higher solar transmissivity of Blue Sage® glazing than 2.0 Sage® one which helps the building to gain more solar energy, as discussed previously. Besides, according to the results, in all cases, 1.24 LNBL is the optimum thermochromic glazing, which may balance the positive effects of solar irradiation in providing some part of the building heating and lighting requirements with its negative effects on the building cooling energy demand.

According to Table 8, which shows the optimum objective functions, the annual total energy consumption in various climate regions decreases from 7.9 to 25.6%, and from 25.8 to 44.0%, for the models with the electrochromic and the thermochromic windows, respectively. Based on the results, as the ANP decision-making method takes all objective functions into account, it results in an optimum design, which is more efficient than the final design of the single-objective optimization method. Besides, it can be concluded that in Iran, thermochromic windows may be a better solution to reduce buildings' energy demand than electrochromic ones, except in the continental region in which both glazings have the same performance. Generally, the results indicate that both the architectural parameters and the climate are important to the extent that the energy performance of a building may be considerably improved by using proper design parameters based on the climatic region.

5. Conclusion

In this research, the energy-saving potential of chromogenic glazings was studied using coupled EnergyPlus - NSGA-II - ANP method in major climate regions of Iran, including continental with dry summer, steppe arid, and arid desert ones. Considering the annual heating, cooling, lighting, and total energy consumption as the objective functions, single and multi-objective genetic algorithms were used to optimize the architectural decision variables, including the building orientation, the window dimensions, and the window optical specifications. Single-objective optimization results showed that the interaction of the objective functions is not predictable. So, the selection of the proper objective function completely depends on the problem. By multi-objective optimization procedure, the annual total energy consumption in various climates decreases from 7.9 to 25.6%, and from 25.8 to 44.0%, in the case of electrochromic and thermochromic windows, respectively. Based on the results, in all cases, the optimum building orientation was almost to the southeast. Moreover, from the desert arid to the continental climates, the optimum WWR increased to provide the building with more solar energy. Besides, in most parts of Iran, thermochromic windows show better performance than electrochromic ones. The developed method and its results may be useful to help to build energy engineers and architects to make the most effective decision on building parameters, which leads to improving the energy efficiency of buildings.

Conflict of Interest

None

Table 8. The optimum building energy consumption using the multi-objective optimization and the ANP decision making approaches

City	Objective Function	Base model (GJ)	Electrochromic Window		Thermochromic Window	
			Optimum model (GJ)	Saving (%)	Optimum model (GJ)	Saving (%)
Tabriz	Annual cooling energy consumption	0.44	0.43	2.3	0.40	9.1
	Annual heating energy consumption	3.05	1.70	44.3	2.30	24.6
	Annual lighting energy consumption	1.93	1.90	1.5	1.15	40.4
	Annual total energy consumption	5.42	4.03	25.6	3.85	29.0
Tehran	Annual cooling energy consumption	1.34	0.70	47.8	1.00	25.4
	Annual heating energy consumption	0.67	1.00	-49.2	0.80	83.3
	Annual lighting energy consumption	1.90	1.90	0.0	1.10	42.1
	Annual total energy consumption	3.91	3.60	7.9	2.90	25.8
Kerman	Annual cooling energy consumption	0.50	0.30	40.0	0.30	40.0
	Annual heating energy consumption	0.70	0.70	0.0	0.80	-14.3
	Annual lighting energy consumption	1.94	1.85	3.6	1.15	40.1
	Annual total energy consumption	3.14	2.85	9.2	2.25	28.3
Bandar-e-Abbas	Annual cooling energy consumption	2.58	1.50	41.9	1.40	45.7
	Annual heating energy consumption	0.00	0.00	0.0	0.04	0.0
	Annual lighting energy consumption	1.92	1.90	1.04	1.08	43.7
	Annual total energy consumption	4.50	3.45	23.3	2.52	44.0

References

[1] Mlyuka NR, Niklasson GA, Granqvist CG (2009) Thermochromic multilayer films of VO_2 and TiO_2 with enhanced transmittance. Sol. Energy Mater. Sol. Cells 93: 1685-1687.

[2] Annual Energy Outlook (2019). U.S. Department of Energy, Washington: DC.

[3] Zarghami E, Azemati H, Fatourehchi D, Karamloo M (2018) Customizing well-known sustainability assessment tools for Iranian residential buildings using Fuzzy Analytic Hierarchy Process. Build. Environ. 128: 107-128.

[4] Jelle BP (2013) Solar radiation glazing factors for window panes, glass structures and electrochromic windows in buildings - measurement and calculation. Sol. Energy Mater. Sol. Cells 116: 291-323.

[5] Favoino F, Fiorito F, Cannavale A, Ranzi G, Overend M (2016) Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates. Appl. Energy 178: 943-961.

[6] Tavares PF, Gaspar AR, Martins AG, Frontini F (2016) Evaluation of electrochromic windows impact in the energy performance of buildings in

Mediterranean climates. Energy Policy 67: 68-81.

[7] Rhodes JD, Gornam WH, Upshaw CR (2015) Using BEopt (EnergyPlus) with energy audits and survey to practical residential energy usage. Energ. Buildings 86: 808-816.

[8] Konstantoglou M, Tsangrassoulis A (2016) Dynamic operation of daylighting and shading systems: A literature review. Renew. Sust. Energ. Rev. 60: 268-283.

[9] Ghosh A, Norton B, Duffy A (2016) Measured thermal performance of a combined suspended particle switchable device evacuated glazing. Appl. Energy 169: 469-480.

[10] Mahdavinejad M, Bemanian M, Khaksar N, Abolvardi G (2011) Choosing efficient types of smart windows in tropical region regarding to their advantages and productivities. Proceedings of the International Conference on Intelligent Building and Management.

[11] Saeli M, Piccirillo C, Parkin IP, Ridley I, Binions R (2010) Nano-composite thermochromic thin films and their application in energy-efficient glazing. Sol. Energy Mater. Sol. Cells 94: 141-51.

[12] Long L, Ye H (2014) Performance demonstration and evaluation of the synergetic application of thermochromic window and phase change material in passive buildings. Energy Procedia 61: 941-944.

[13] Allen K, Connelly K, Rutherford P, Wu Y (2017) Smart windows - Dynamic control of building energy performance. Energ. Buildings 139: 535-546.

[14] Deb SK, Photovoltaic-integrated electrochromic device for smart-window applications. Proceedings of the 6th Conference of National Renewable Energy Laboratory, (2000).

[15] Sbar NL, Podbelski L, Yang HM, Pease B (2012) Electrochromic dynamic windows for office buildings. Int. J. Sustainable Built. Environ. 1: 125-139.

[16] DeForest N, Shehabi A, O'Donnell J, Garcia G, Greenblatt J, Lee ES, Selkowitz S, Milliron DJ (2015) United States energy and CO_2 savings potential from deployment of near-infrared electrochromic window glazings. Build. Environ. 89: 107-117.

[17] DeForest N, Shehabi A, Selkowitz S, Milliron DJ (2017) A comparative energy analysis of three electrochromic glazing technologies in commercial and residential buildings. Appl. Energy 192: 95-109.

[18] Nguyen AT, Reiter S, Rigo P (2014) A review on simulation-based optimization methods applied to building performance analysis. Appl. Energy 113: 1043–1058.

[19] Yi H, Srinivasan RS, Braham WW (2014) An integrated energy-energy approach to building form optimization: use of EnergyPlus, energy analysis and Taguchi-regression method. Build. Environ. 84: 89-104.

[20] Delgarm N, Sajadi B, Azarbad Kh, Delgarm S (2018) Sensitivity analysis of building energy performance: A simulation-based approach using OFAT and variance-based sensitivity analysis methods. Journal of Building Engineering 15: 181-193.

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

[22] Rapone G, Saro O (2012) Optimisation of curtain wall Facades for office buildings by means of PSO algorithm. Energ. Buildings 45: 189-196.

[23] Joe J, Choi W, Kwak Y, Huh JH (2014) Optimal design of a multi-story double skin façade. Energ. Buildings 76: 143-150.

[24] Holst JN (2003) Using whole building simulation models and optimizing procedures to optimize building envelope design with respect to energy consumption and indoor environment. Proceedings of the 8th International Conference of IBPSA.

[25] Delgarm N, Sajadi B, Kowsary F, Delgarm S (2016) Multi-objective optimization of the building energy performance: A simulation-based approach by means of particle swarm

optimization (PSO). Appl. Energy 170: 293-303.

[26] Delgarm N, Sajadi B, Delgarm S, Kowsary F (2016) A novel approach for the simulation-based optimization of the buildings energy consumption using NSGA-II: Case study in Iran. Energ. Buildings 149: 552-560.

[27] Deb K, Pratap A, Agarwal S, Meyarivan T (2002) A fast and elitist multi-objective genetic algorithm: NSGA-II. IEEE Trans. Evol. Comput. 6: 181-197.

[28] Machairas V, Tsangrassoulis A, Axarli K (2014) Algorithms for optimization of building design: A review. Renew. Sust. Energ. Rev. 31: 101-112.

[29] Triantaphyllou E, Mann SH (1995) Using the analytic hierarchy process for decision making in engineering applications: Some challenges. Int. J. Ind. Eng. Appl. P. 2: 35-44.

[30] Saaty LT (1980) Decision making with the Analytic Network Process. Internat. Ser. Oper. Res. Management Sci. 95: 1-26.

[31] Iranian National Building Code: Part 19 (2010), Ministry of Road and Urban Development, Tehran.

[32] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World Map of the Köppen-Geiger climate classification updated. Meteorol. Z. 15: 259-263.

[33] 2017 ASHRAE Handbook-Fundamentals: Chapter 14 (2017). ASHRAE, Atlanta: GA.