Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 7, S. 227-232, 3, 2023
© Telif hakkı IJANSER'e aittir
Araştırma Makalesi

IJANSER
https://as-proceeding.com/index.php/ijanser
ISSN: 2980-0811

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 7, pp. 227-232, 3, 2023
Copyright © 2023 IJANSER
Research Article

The optimization of a residential building envelope using particle swarm method in a warm climate

Kaan Yaman*[,1] and Gökhan Arslan[2]

[1]*Department of Mechanical Engineering, Mersin University, 33343 Mersin, Turkey*
[2]*Department of Mechanical Engineering, Mersin University, 33343 Mersin, Turkey*

(yamankaan@mersin.edu.tr) Email of the corresponding author

(Received: 25 March 2023, Accepted: 11 April 2023)

(2nd International Conference on Engineering, Natural and Social Sciences ICENSOS 2023, April 4 - 6, 2023)

ATIF/REFERENCE: Yaman, K. & Arslan, G. (2023). The optimization of a residential building envelope using particle swarm method in a warm climate. *International Journal of Advanced Natural Sciences and Engineering Researches*, 7(3), 227-232.

***Abstract* –** Energy efficiency in buildings requires an optimization process to reduce energy needs without sacrificing comfort conditions. In this study, a residential building was considered and optimum envelope design options were determined by the particle swarm optimization. Two case were created to evaluate the design options depending on the building orientation. It is shown that the optimum envelope design depending on the building orientation partially affects the energy consumption and has a significant effect on thermal comfort. Finally, it has been shown that the optimum solutions by sensitivity analysis were also applicable in Adana climate conditions.

Keywords – Cooling Load; Heating Load; Thermal Comfort; Building Orientation, Optimization.

I. INTRODUCTION

While the global energy consumption originating from buildings is between 20-40%, this rate is 35% in Turkey according to the data of the General Directorate of Energy Affairs [1,2]. Despite their high energy consumption values, buildings also have a high saving potential. Energy saving in buildings requires an optimization process that meets the objectives in many areas such as climate conditions, user parameters, and material properties without sacrificing comfort conditions.

Some important studies in the literature for the aforementioned reason are as follows: Ferrara et al. [3] stated optimum solutions that maximize thermal comfort conditions with a slightly smaller increase in energy consumption in a school building. Delgarm et al. [4] investigated multi-objective optimum design options according to many envelope design parameters such as building orientation, sunshade and window size, glass, and wall properties. As a result, they emphasized that the annual total building energy consumption decreased by 1.6-11.3% and that climatic conditions were important in determining the building energy performance. A similar study was done by Tuhus-Dubrow and Krarti [5]. They [5] observed that rectangular and trapezoidal-shaped buildings performed best in the five different climatic zones. On the other hand, Lartigue et al. [6] presented multi-purpose optimum design options to reduce energy demand and increase daylight saving time.

As it can be understood from some other important studies [7–9], the literature shows that the most important factor in building energy saving is the envelope design parameters of the building, and more study needs to be done in this regard. For this reason, this study was carried out to increase the number of studies on the optimization of building envelope design. In this study, it is aimed to create design options and decision support for different purposes for a residential building located in a warm climate zone. More specifically, in this study, the effect of building orientation on the envelope design was investigated. For this purpose, firstly, the optimization process was carried out for the same architectural design features in every orientation of the building. Then, this optimization process was repeated for four different orientations of the building. Finally, a sensitivity analysis was performed to determine the effect of climate on optimum solutions.

II. PROBLEM DESCRIPTION

A single-family, villa-type residential building is considered for the building envelope optimization problem. The isometric view of the building is given in Fig. 1. EnergyPlus© (v8.4) program was used to model the building features and the HVAC system. The building was located in Mersin (36.4° N, 33.9° E), where is a warm climate zone. Here, the annual heating and cooling degree-days are 789 and 874, respectively. Typical Meteorological Year (TMY) climate data was used.

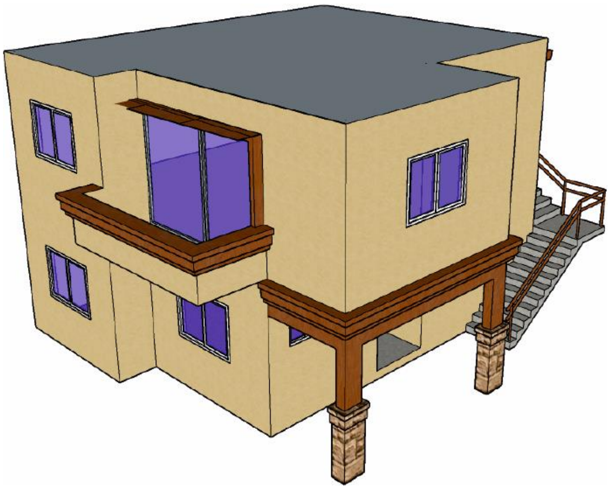

Fig. 1 Isometric view of the building.

The building form tends to increase heat transfer. There is a mezzanine room and two balconies on the first floor, changing the rectangular form of the building. The building's floor height is 2.8 m and its gross volume is 360.4 m^3. In addition, the outer wall surface area is 166.2 m^2 and the window area is 28.1 m^2. The ratio of the window surface area to the wall surface area is 0.124 m^2/m^2 for the south façade, 0.083 m^2/m^2 for the north façade, 0.195 m^2/m^2 for the east façade, and 0.191 m^2/m^2 for the west façade. The sample building floor plan is given in Fig. 2.

The building was air-conditioned with two different HVAC systems placed in each zone. A packaged terminal air conditioner (PTAC) with a COP value of 3 was used as the cooling system, and a natural gas-fired baseboard hot water system operating with 90% efficiency was used as the heating system. The parameters for the building, such as occupancy density, internal heat gains, etc. were taken from a previous study of the authors [10]. Table 1 is summarized these parameters.

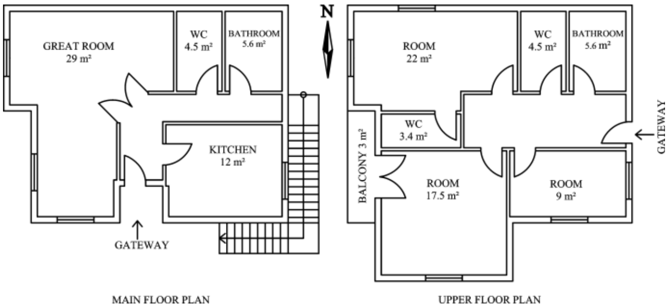

Fig. 2 Floor plan of the building.

Table 1. Characteristics of the building system.

Parameters				Unit
Comfort temperature	20 (heating) 23 (cooling)			°C °C
HVAC	Heating supply Cooling supply	Baseboard PTAC	Efficiency=0.8 COP=3	
Schedule	Weekdays Weekend	5 p.m. – 8 a.m. 8 a.m. – 5 p.m.		
Ventilation	0.8 (natural)			hr^{-1}
People density	0.05			Person/m^2
Lighting density	10			W/m^2
Other equipment	2.5			W/m^2

Two cases were examined within the scope of the study. It was aimed to determine common and different optimum envelope design solutions for each orientation of a building for case#1 and case#2, respectively. Thus, a methodology is developed to determine optimum design options based on the building orientation.

A. *Particle Swarm Optimization*

In this paper, PSO was used, which was first introduced by Kennedy and Eberhart [11,12] and later developed by Clerc and Kennedy [13] with a contraction coefficient algorithm. PSO is a population-based optimization method inspired by the social behavior of bird and similar species. Particles in the population randomly generated by the PSO algorithm update their velocities (v) and positions (x) using Eqs. (1) and (2), respectively.

$$v_i^{k+1} = X\left[v_1^k + c_1\varphi_1^k\left(p_{l,i}^k - x_i^k\right) + c_2\varphi_2^k\left(p_{g,i}^k - x_i^k\right)\right] \quad (1)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (2)$$

where i is the number of particles and k is the number of iterations. φ_1 and φ_2 are randomly generated number values between 0 and 1. Learning coefficients were taken as $c_1 = c_2 = 2.05$ as suggested by Ref. [14]. PSO performance is improved by controlling the particle velocity with the contraction factor χ and can be found with Eq. (3) [15].

$$\chi = \frac{2}{\left|2-\omega-\sqrt{\omega^2-4\omega}\right|}, \quad \text{if} \quad \omega > 4 \quad (3)$$

where $\omega = c_1 + c_2$. Particles update their velocity and position according to the best solution in the population. In this way, the generations are updated and the optimum values are determined. In the PSO algorithm, the number of particles and generations is limited to 20. GenOpt® (v3.1) software, which can work on a based simulation, was used to solve the optimization problem. GenOpt was chosen because it can work integrated with EnergyPlus. More detailed information can be found in Ref. [16].

B. *Decision Variables*

The optimization problem is handled with six different continuous values depending on the insulation thickness, glass surface area, sunshade properties, and two different discrete values depending on the reflectivity ratio of the surfaces, as well as different building topologies for the wall, roof, and window. Thus, a total of 11 optional, discrete, and continuous values were considered as decision variables. Value ranges and other details for different decision variables in Tables 2 and 3 were shown.

C. *Objective Function*

In this study, it is aimed to minimize the building's primary energy need due to the annual heating and cooling load. Therefore, the weighted sum method is used to obtain an optimum single solution. Accordingly, the objective function (F) is defined as follows:

$$\text{min: } F(\vec{x}) \triangleq \omega \sum_{i=1}^{2} \frac{f_i(\vec{x})-f_i^U(\vec{x})}{f_i^N(\vec{x})-f_i^U(\vec{x})} \quad (4)$$

where $\vec{x}$ is the decision variables vector, and $f_1(\vec{x})$ and $f_2(\vec{x})$ represent the heating and cooling loads, respectively. N and U upper indices show upper and lower limit values, respectively. Finally, the objective function weight (ω) were taken equally, namely $\omega = 0.5$.

Table 2. Independent parameters in the building envelope design.

Parameter	Initial value	Range	Units
Wall construction typology	WC1	WC1, WC2, WC3	n/a
Roof construction typology	RC1	RC1, RC2	n/a
Window typology	W1	W1, W2, W3, W4	n/a
Thickness of insulation on wall	0.015	Max. U=0.66 W/m^{2}K [17]	m
Thickness of insulation on roof	0.02	Max. U=0.43 W/m^{2}K [17]	m
Width of glazed area	1.6	0.5 – 3.4	m
Height of glazed area	1.2	0.5 – 2.0	m
Depth of overhang shading	0.3	0.0 – 1.0	m
Slope of overhang shading	90	0 – 90	deg
Wall reflectivity	0.3	0.01, 0.02–0.90	-
Roof reflectivity	0.3	0.01, 0.02–0.90	-

Table 3. Envelope and window types description (m).

Item	Layers[a]			
WC1	Plaster 0.02, EPS 0.015, Brick 0.19, Gypsum plaster 0.02			
WC2	Plaster 0.02, Gas concrete 0.20, Gypsum plaster 0.02			
WC3	Plaster 0.02, Polystyrene foam 0.015, Brick 0.19, Gypsum cardboard plate 0.008, Gypsum plaster 0.02			
RC1	Sandy-pebbly mosaic 0.01, Cement screed 0.05, EPS 0.02, Reinforced concrete 0.1, Gypsum plaster 0.02			
RC2	EPDM, Cement screed 0.05, Polystyrene foam 0.02, Concrete 0.1, Plasterboard 0.008, Gypsum plaster 0.02			
		SHGC	τ	U-value
W1	PVC 0.04; Glass 0.003, Air 0.006, Glass 0.003	0.762	0.812	3.122
W2	PVC 0.04; LowE glass 0.006, Air 0.006, Glass 0.006	0.569	0.745	2.371
W3	PVC 0.04; LowE glass 0.006, Air 0.013, Glass 0.006	0.568	0.745	1.761
W4	PVC 0.04; Glass 0.003, Air 0.006, Glass 0.003, Air 0.006, Glass 0.003	0.682	0.738	2.143

[a] The layers were ordered from outside to inside.

D. *Constrains*

The following two important constraints were applied to reduce building energy consumption values: (i) overall heat transfer coefficients that should be accepted as the maximum value for the building elements by the TS825 [17], and (ii) thermal comfort is guaranteed. The maximum overall heat transfer coefficients defined according to the TS825 [17] were given in Eqs. (5) and (6) for the wall and roof, respectively.

$$U_{wall} \leq 0.66 \tag{5}$$
$$U_{roof} \leq 0.43 \tag{6}$$

where U is the overall heat transfer coefficient.

Building energy performance needs to be increased without compromising comfort conditions. Therefore, the objective function was constrained to a maximum of 15% of the predicted percent of dissatisfied (PPD) proposed by Fanger [18] and later standardized by the ISO. PPD is determined by Eq. (7).

$$PPD = 100 - 95\exp(-0.03353PMV^4 - 0.2179PMV^2) \tag{7}$$

E. *Sensitivity Analysis*

A sensitivity analysis was conducted to determine the effect of climate on the optimum solutions reached in a given climatic condition. Sensitivity analysis was carried out for Adana, Antalya, Izmir, and Mugla located in the warm climate zone. In the analysis, the sensitivity index was given in Eq. (8) was used [19].

$$\delta f = (f_{max} - f_{min})/f_{max} \tag{8}$$

III. SIMULATION RESULTS AND DISCUSSIONS

In this study, optimum design solutions for the envelope of a residential building were determined. In this context, two cases were created to evaluate the effect of building orientation on the architectural design of the envelope. In Fig. 3, the optimization process of a residential building in case#1 and case#2 is presented in each iteration. Here, each iteration shows the building envelope design solutions. According to the objective function defined by Eq. (4), the optimum energy consumption value was 391.4 kWh/m^2/y for case#1 and 380.7 kWh/m^2/y for case#2. Accordingly, the total energy consumption value of the building was decreased by 8.6% and 11.1% in the case#1 and case#2, respectively. However, while the thermal discomfort was 14.9% in case#1, this value was 12.3% in case#2. While the case#2 partially was reduced the energy consumption value of the building compared to the case#1, it was more effective in the rate of thermal comfort. It has been concluded that the envelope designs to be made according to the building directions can increase the thermal comfort as well as reduce the energy consumption value of the building.

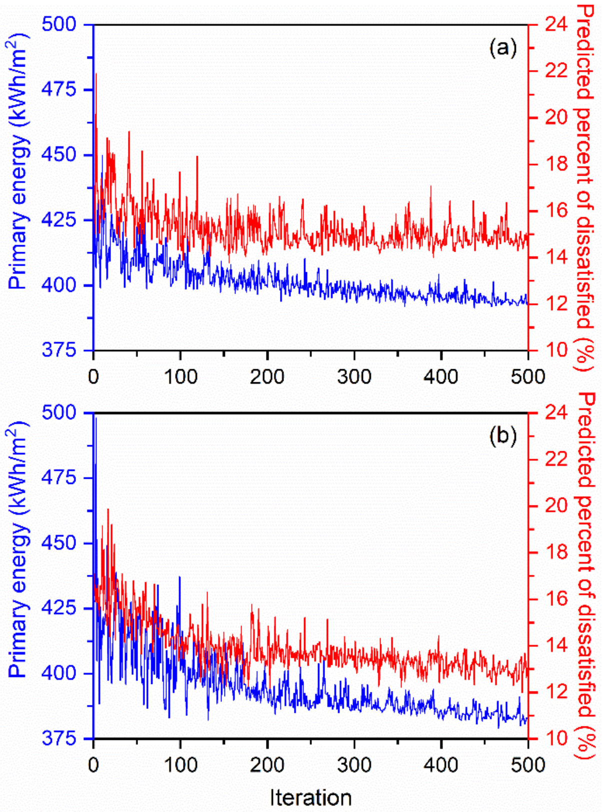

Fig. 3 The optimization process of the building envelope design at each iteration: (a) for case#1 and (b) for case#2.

Table 4 shows the optimum design solutions for the building envelope. For optimum designs, D2 type wall without additional thermal insulation was determined. However, a D3 type wall was proposed for the west façade in the case#2. This was due to the thermal mass of the wall, as well as the tendency of the outside air temperature to increase and decrease during the day, and the effect of solar radiation on the west façade. As a matter of fact, the same was true for the window type. In the case#1, the roof insulation thickness was approximately 1 cm less than case#2, and the reflectivity ratio was 0.9. Moreover, in the case#2, the wall surface reflectivity ratios are 0.82 for the highest south façade and 0.10 for the lowest east façade. Other proposed design parameters were summarized in Table 4.

Table 4. Building envelope optimum design solutions.

Parameter	Case#1	Case#2				Units
		S	E	W	N	
Wall construction typology	WC2	WC2	WC2	WC3	WC2	n/a
Roof construction typology	RC1	RC2	RC2	RC2	RC2	n/a
Window typology	W3	W3	W2	W3	W3	n/a
Thickness of insulation on wall	-	-	-	0.021	-	m
Thickness of insulation on roof	0.07	0.078	0.078	0.078	0.078	m
Width of glazed area	1.17	1.45	1.09	1.05	0.58	m
Height of glazed area	1.24	2.89	1.35	1.77	1.74	m
Depth of overhang shading	0.46	0.17	0.34	0.98	0.99	m
Slope of overhang shading	21.2	54.4	50.6	44.6	29.9	deg
Wall reflectivity	0.51	0.82	0.10	0.67	0.42	-
Roof reflectivity	0.90	0.85	0.85	0.85	0.85	-

Fig. 4 shows the results of the sensitivity analysis. Accordingly, it is seen that the obtained optimum solutions were more applicable in Adana climate conditions compared to other regions. In Antalya climatic conditions, the standard deviation was the highest with 0.0629.

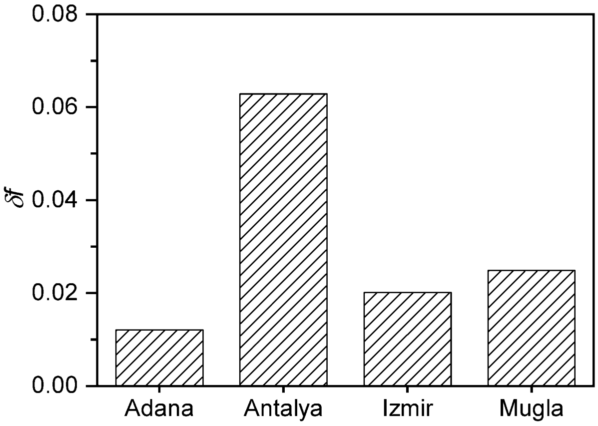

Fig. 4. Sensitivity indexes of optimum envelope design for different warm climate regions.

IV. CONCLUSIONS

Buildings have a significant share of global and national energy consumption and the necessity of reducing this is widely known. Energy efficiency in buildings requires an optimization process to reduce energy needs without sacrificing comfort conditions. In this study, a single-family villa-type residential building was considered and optimum envelope design options were determined by the PSO algorithm. Two cases were created to evaluate the design options depending on the building orientation. While the annual optimum energy consumption value for case#1 was 391.4 kWh/m^2/y, thermal discomfort was determined as 14.9%. For case#2, the optimum annual energy consumption and thermal discomfort are 380.7 kWh/m^2/y and 12.3%, respectively. As a result, it was shown that the optimum envelope design depending on the building orientation partially affects the energy consumption (2.7%) and has a significant effect on thermal comfort (2.6%). Finally, it has been shown that the optimum solutions by sensitivity analysis were also applicable in Adana climate conditions.

REFERENCES

[1] Pérez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy Build 2008;40:394–8.

[2] EIGM. TC Enerj İşleri Genel Müdürlüğü 2016. http://www.eigm.gov.tr/tr-TR/DengeTablolari/Denge-Tablolari.

[3] Ferrara M, Filippi M, Sirombo E, Cravino V. A simulation-based optimization method for the integrative design of the building envelope. Energy Procedia 2015;78:2608–13.

[4] Delgarm N, Sajadi B, Kowsary F, Delgarm S. Multi-objective optimization of the building energy

performance: A simulation-based approach by means of particle swarm optimization (PSO). Appl Energy 2016;170:293–303.

[5] Tuhus-Dubrow D, Krarti M. Genetic-algorithm based approach to optimize building envelope design for residential buildings. Build Environ 2010;45:1574–81.

[6] Lartigue B, Lasternas B, Loftness V. Multi-objective optimization of building envelope for energy consumption and daylight. Indoor Built Environ 2014;23:70–80.

[7] Yaman K, Arslan G. Analysis of annual energy requirement of a residential house with TS825 and ASHRAE heat balance methods. Turkish J Eng 2017;1:5–10.

[8] Akan AE, Ünal F, Koçyiğit F. Investigation of Energy Saving Potential in Buildings Using Novel Developed Lightweight Concrete. Int J Thermophys 2021;42:4.

[9] Koçyiğit F, Ünal F, Koçyiğit Ş. Experimental analysis and modeling of the thermal conductivities for a novel building material providing environmental transformation. Energy Sources, Part A Recover Util Environ Eff 2020;42:3063–79.

[10] Yaman K, Arslan G. The impact of hourly solar radiation model on building energy analysis in different climatic regions of Turkey. Build Simul 2018;11:483–95.

[11] Kennedy J, Eberhart R. Particle swarm optimization. Proc. ICNN’95 - Int. Conf. Neural Networks, vol. 4, IEEE; 1995, p. 1942–8.

[12] Kennedy J, Eberhart RC. Discrete binary version of the particle swarm algorithm. Proc IEEE Int Conf Syst Man Cybern 1997;5:4104–8.

[13] Ozkaya, U., Seyfi, L. Optimal Rectangular Microstrip Antenna with and without Air Gaps Design by Means of Particle Swarm Optimization and Vortex Search Algorithm. International Journal of Computer and Communication Engineering, 6(1) (2017), 75.

[14] M. Clerc, J. Kennedy, The particle swarm – explosion, stability, and convergence in a multidimensional complex space, IEEE Transactions on Evolutionary Computation 6 (2002) 58–73.

[15] M. Clerc The swarm and the queen: towards a deterministic and adaptive particle swarm optimization Proc. 1999 ICEC, Washington, DC (1999), pp. 1951–1957.

[16] ABD Enerji Bakanlığı bünyesindeki Lawrence Berkeley National Laboratory’de 1998 n.d.

[17] TS825: Thermal Insulation Requirements for Buildings 2013.

[18] Fanger, P.O. 1970. Thermal Comfort-Analysis and Applications in Environmental Engineering, Danish Technical Press, Copenhagen. n.d.

[19] Hamby DM. A review of techniques for parameter sensitivity analysis of environmental models. Environ Monit Assess 1994;32:135–54.