BNUT

Iranian (Iranica) Journal of Energy & Environment
Journal Homepage: www.ijee.net
IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

Optimization of Residential Spatial Configuration based on Energy Performance, Daylight Brightness, and Thermal Comfort through Pareto Evolutionary Algorithm, Case Study: Mashhad City Climate

J. Ahmadi[1], S. M. Maddahi[2]*, R. Mirzaei[1]

[1] *Department of Architecture, Birjand Branch, Islamic Azad University, Birjand, Iran*
[2] *Department of Architecture, University of Science and Industry, Tehran, Iran*

P A P E R I N F O

Paper history:
Received 08 November 2022
Accepted in revised form 20 February 2023

Keywords:
Daylight
Energy performance
Functional computational design
Performance optimization
Thermal comfort

A B S T R A C T

All important decisions that affect the thermal performance of the building are made in the early stages of design. Accordingly, in this research, the initial stage of architectural design which is related to space plan was targeted. The aim of this research is the perfect approach to evaluate, and optimize the energy a set of alternative spatial layout solutions through the functional computational design model. The method of this research includes the production of coherent design solutions and the evaluation and optimization of the energy performance of the selected solutions. In the first part, space allocation at a level produces the plan through an evolutionary technique. In the next step, certain plans were evaluated for energy performance, performance rank, and optimization. The energy simulation tool is Honeybee and Ladybug plugins,. The optimization tool is Pareto Evolutionary Algorithm in the Octopus plugin. The reproduction rate, the mutation rate and the possibility of mutation were 0.9, 0.8 and 0.2, respectively. The results showed that each algorithm is a suitable tool for design solutions, thermal performance of floor plans, helping architects' perspective in the decision-making process, and speeding up the design process. Finally, based on the optimization, the final result of the research algorithm is 70 elite answers in the Pareto front. Only during the Pareto front optimal responses, energy consumption can be reduced by more than 30%; in daylight time and more than 39% improvement was achieved.

***doi**: 10.5829/ijee.2023.14.03.05*

INTRODUCTION

In general, one-third of the total energy in most countries is related to the building sector [1], and a major share of energy consumption in buildings is related to residential buildings [2]. With an increase in the world's population and, as a result, the growing trend of the construction of residential spaces, housing can be introduced as one of the most important sectors determining the world's energy. The use of energy performance simulation in the design process can be effective in the efficiency of energy consumption and the comfort of residents; but, the use of simulation software is not common among designers. They mainly rely on their past experiences or rule-based approaches [3]. The reason for this is the complexity of using simulation programs, such as the correct construction of simulation models, the specialization of interpreting the results, the long time of the simulation process in an architectural design process, and compatibility problems with common design software [4].

In addition, different design and energy performance goals are contradictory in some cases [5], and reaching the optimal response between them is very complicated [6]. Also, these approaches focus on the final design phases, while all the important decisions that affect the thermal performance of the building are made in the early phases. Therefore, it is necessary to define a method to evaluate residents' energy performance and comfort in the early phases of design, including conceptual design,

*Corresponding Author Email: sm.madahi@gmail.com (S. M. Maddahi)

Please cite this article as: J. Ahmadi, S. M. Maddahi, R. Mirzaei, 2023. Optimization of Residential Spatial Configuration based on Energy Performance, Daylight Brightness, and Thermal Comfort through Pareto Evolutionary Algorithm, Case Study: Mashhad City Climate, Iranian (Iranica) Journal of Energy and Environment, 14(3), pp. 228-239. Doi: 10.5829/ijee.2023.14.03.05

planning, and space layout [7]. Based on this, the approach of functional computation design in the phase of space layout and planning of spaces can be a suitable response to this issue. Computational design synthesis has been applied in architecture since the 1960s [8]. Reported efforts for functional computational architecture in the space layout design process have started since the 1970s [5].

This problem is inherently discrete and multi-objective. Due to its combinatorial complexity, it cannot be completely solved for layout problems of reasonable size. Several heuristic strategies have been developed to find solutions without exhaustively searching the design space [9]. Based on the review of the background of spatial configuration generative design, in general, automatic configuration generation methods can be divided into four general groups, including area-oriented design [10], network-oriented design [11], topological design [12] and mixed methods [13].

In the functional computational design of spatial configuration, various architectural factors such as building form features [14], building orientation angle [15], and building wall features should be considered. Also, in order to examine the energy performance of the building, various functional goals such as thermal demand [16], lighting demand [17], and ventilation demand [18] should be examined. Also, for optimization-based calibration, genetic algorithm (GA) [19, 20], particle swarm optimization (PSO) [21, 22] and the Hooke and Jeeves (HJ) algorithm [23, 24], are the most widely used algorithms.

In the process of functional computational architecture, optimization algorithms are used in the process in order to optimize functional goals, such as energy requirements, thermal comfort, and daylight illumination, and in order to examine a large set of responses in a short time [7] and evolutionary algorithms are a type of optimization algorithms based on Darwin's theory of evolution [25]. One of the types of Multi-objective Optimization Evolutionary Algorithm (MOEA) is Strength Pareto Evolutionary Algorithm 2 (SPEA2) [7], which was designed and presented by Zitzler et al. [26] and presented a multi-objective structural genetic algorithm. SPEA2 provides good performance in terms of convergence and variety [27].

Based on what was stated, the purpose of this study was to build an automatic configuration design algorithm with an area-oriented approach, optimizing the residential spatial configuration based on energy performance, daylight illumination, and thermal comfort through SPEA2 and evaluating the results obtained from the designed algorithm with statistical tests in the climate and geography of Mashhad. The increasing collective growth, the growing construction trend, and the socio-political situation of Mashhad have been among the main reasons for choosing this location to conduct the present research.

METHODOLOGY

The method of this study, with a quantitative approach, is the coding of a generative design algorithm based on the layout of spaces, simulation, and optimization in an apartment unit situated in Mashhad. Also, the evaluation of the final results of the algorithm is performed by a quantitative approach and through correlation and regression tests. The research location is Mashhad city, and the statistical population is the space layout of possible residential units with dimensions of 90 m^2. The research method includes three general parts: the space layouts coding process, the performance optimization process, and the Pareto front results evaluation process. Sampling in coding is automatically targeted in the optimization section according to the settings of SPEA2. The results of evaluation section was in the form of Pareto front optimization. Research tools were the Grasshopper software and Python programming language in the Grasshopper platform in the coding section, Honeybee and Ladybug plugins in the Grasshopper platform in the optimization section, and SPSS software in the evaluation of the results section. The selection of steps in the optimization algorithm is based on the literature of the research, due to reaching a comprehensive range of answers and an optimal number of configuration examples.

The spatial configuration coding process

In the space layout coding process, the area of the desired residential unit is considered to be 90 m^2. In the assumption of the research, all the spaces of the residential unit are defined as rectangular and in the longitudinal and transverse axes of the residential unit. Based on the studies conducted on the residential units of Mashhad city, six spaces have been considered in the residential unit, including a kitchen, reception, WC, bathroom, and two bedrooms next to an entrance. In order to define the minimum dimensions of the spaces, first through the criteria of the Road, Housing and Urban Development Research Center [28], the standards of the minimum dimensions of each space have been obtained. Then through the Delphi technique and by open questionnaire and interview, its validity has been confirmed by experts.

In order to reach the possible area of the spaces in the algorithm, assuming the existence of n spaces (a, b, c, ..., n), the maximum possible area of the space (a) in the total area (S_{all}) based on the minimum standard surface area obtained of each space is achieved according to the following formula:

$$Max\left(Est.S_{Space(a)}\right) = S_{all} - \sum_{i=1}^{n-1} Min\left(Sta.S_{Space(i)}\right) \qquad (1)$$

based on this, based on the total area of 90 m^2 and with six spaces, the maximum area of one space (a) is obtained according to the following formula based on the minimum standard area of other spaces (i):

$$Max\left(Est.S_{Space(a)}\right) = 90m^2 - \sum_{i=1}^{5} Min\left(Sta.S_{Space(i)}\right) \quad (2)$$

After entering the formulas in the coding process, the maximum possible area of each space is obtained. Based on this, the area of each residential space is determined.

The range of each area, according to the following formula, due to the consideration of the area of the building walls and possible communication spaces based on the opinion of experts, becomes a smaller range. The Equations (3) and (4) defines the final minimum and maximum area. In these formulas, the maximum possible area of each space (Sta. S_{Space}(a)) in 90 m^2 will be obtained based on the minimum-maximum estimated area of that space (Sta. S_{Space}(a)) and the minimum standard area of that space (Sta. S_{Space}(a)).

$$Max\left(Poss.S_{Space(a)}\right) = Max\left(Est.S_{Space(a)}\right) - \left[\left(Max\left(Est.S_{Space(a)}\right) - Min\left(Sta.S_{Space(a)}\right)\right) \times 0.25\right] \quad (3)$$

$$Min\left(Poss.S_{Space(a)}\right) = Min\left(Est.S_{Space(a)}\right) + \left[\left(Max\left(Est.S_{Space(a)}\right) - Min\left(Sta.S_{Space(a)}\right)\right) \times 0.25\right] \quad (4)$$

The final result is the possible lengths and widths for the possible area of the rectangle suitable for each use and, as a result, the range of possible side lengths of that rectangle. In the following, the different modes of all residential spaces are drawn on the zero-zero coordinate axis. In the next phase, all the spaces formed for each configuration must be placed together based on the criteria desired by the designer. In order to determine and define the spaces adjacent to each other in the plan, the adjacency matrix of the spaces has been determined. Then its validity was confirmed by experts through the Delphi technique, open questionnaire, and interview.

Python code has been written to place the spaces together based on the adjacency matrix. The process of placing spaces together continues until all spaces are placed together. In order to approach the overall form of the plan to a rectangular shape, the entire plan is enclosed in the smallest possible rectangle. The empty spaces between the interior spaces and between the plan and the enclosed rectangle are added to the side spaces until the total area of 90 m^2 is reached.

The process of optimizing energy performance, daylight illumination, and thermal comfort

In order to optimize the energy performance, it is first necessary to determine the energy and climate-geographical simulation settings to define the model. For this purpose, first environmental comfort conditions, including thermal comfort, lighting, and ventilation, are studied. The geographical territory of this study was Mashhad city, and based on the Köppen classification, Mashhad has a cold and dry climate. In order to check the thermal comfort, the predicted mean vote (PMV) index, a value between -3 and +3, has been used, and the standard amount for residential spaces is determined between -0.5 and 0.5.

In this study, the cooling set point is 24°C, and the cooling blocking point is 30°C. The heating set point is 18°C and the heating blocking point is considered to be 15°C. Lighting comfort is based on the lighting intensity of different residential spaces with luxury units in the National Illumination Committee of Iran. Based on this, the lighting set point determines the amount of light sufficient to turn on and off the electric lights, and in this study, 300 lux is considered.

In the following, the building settings for energy simulation (Energy Set points) have been determined by examining the research background. Then, to check validity, it has been confirmed by experts in the energy field. The minimum height of the rooms, kitchen, and living spaces is considered to be a minimum of 2.7 m and a maximum of 3.6 m, and the minimum height of the WC is 10.2 m and a maximum of 3 m with a step of 0.2 m. Windows are considered in the middle of the outer side of each space and determined according to the following settings. According to the settings, the total area of the windows of each room should not be less than 8% of the area of that room, and the area of any window should not be less than 50 cm^2. The minimum area of the window is 8% of the room area, and its maximum is 60%, with a step of 5%. The windows have been checked in the north, south, east, west, and 30 and 60 degrees northeast, northwest, southeast, and southwest orientations. The windows are designed in three ways: one piece, two pieces, and three on each side of the facade. The specifications of the materials used in the ceiling for simulation is stated in Table 1.

Table 1. Specifications of the materials used in the ceiling for simulation

Option	Specification of ceiling materials	Thickness	U-value
1	Mosaic, cement-sand mortar, wind-blown sand, asphalt felt, sloped concrete, joist, Plaster-soil mortar	50 cm	1.6
2	Mosaic, polystyrene, cement-sand mortar, wind-blown sand, asphalt felt, sloped concrete, joist, Plaster-soil mortar	53 cm	0.346
3	Mosaic, cement-sand mortar, concrete with mineral pumice and cement, concrete slab, metal hole, steel sheet	50 cm	0.45
4	Mosaic, cement-sand mortar, concrete with mineral pumice and cement, concrete slab, metal hole, steel sheet	50 cm	0.22

The window sill level (OKB) in all spaces, except for the WC and bathroom, are considered from 80 cm to 1.1 m with a step of 0.1 m, and the distance between the windows on both sides is a minimum of 50 cm and a maximum of 2 m with a step of 0.2 m. In the bathroom and WC, the minimum window sill level (OKB) is 1.5 m and the maximum is 2.2 m. The length and height of the window, except for the bathroom and WC, are set at a minimum of 0.5 m and a maximum of 2 m with a step of 0.2 m, and for WC and bathrooms, a minimum of 0.2 m and a maximum of 0.5 m. The specifications of the materials used in the exterior wall for simulation is listed in Table 2.

Table 2. Specifications of the materials used in the exterior wall for simulation

Option	Specifications of wall materials	Thickness	U-value
1	Plaster-soil mortar, solid brick, cement-sand mortar, facade stone	30 cm	1.5
2	Plaster-soil mortar, clay block, cement-sand mortar, facade stone	21 cm	1.3
3	Plaster-soil mortar, clay block with polystyrene insulation, cement-sand mortar, facade stone	21 cm	1.08
4	Plaster-soil mortar, Leca block, cement-sand mortar, stone facade	28 cm	1.34
5	Plaster-soil mortar, Leca block, space filled with polystyrene, Leca block, sand-cement mortar, facade stone	33 cm	0.41
6	Plaster-soil mortar, HEBELEX block, cement-sand mortar, facade stone	28 cm	0.71
7	Plaster-soil mortar, HEBELEX block, space filled with polystyrene, HEBELEX block, cement-sand mortar, facade stone	33 cm	0.37

Table 3. Specifications of the materials used in the interior wall for simulation

Option	Specifications of wall materials	Thickness	U-value
1	Plaster-soil mortar, brick, plaster, and soil	16 cm	3.8
2	Plaster wall	10.3 cm	3.4
3	Plaster-soil mortar, HEBELEX block, Plaster-soil mortar	16 cm	1.2
4	Plaster-soil mortar, Leca block, Plaster-soil mortar	16 cm	0.8

This section of Iran's common materials class presents the specifications of the materials used in the simulation. The selected materials were selected based on field study and research background and were approved by experts for validity. The ceiling and floor materials are determined into four types. For the exterior wall of the building, seven types of common materials in the construction industry of Iran have been determined. Also, four types of interior wall materials have been defined. The specifications of the materials used in the interior wall for simulation stated in Table 3.

Also, eight types of thermal break and UPVC windows have been determined. The specifications of the materials used for the windows for simulation is listed in Table 4.

Also, some samples of common materials have been considered for the canopy. Exterior canopy materials include four options: brick, wood, steel, and PVC. The canopy angle is also determined from zero to 90 degrees with a step of 10 degrees for the algorithm. The type of exterior canopy is defined in two types, horizontal and general, and is optimized. Also, a set of alternatives for floor, wall, and ceiling has been considered for elaborate work. In the meantime, wood parquet, brick, and concrete are used for flooring, white plaster, brick design, gray

Table 4. Specifications of the materials used for the windows for simulation

Window type	Options	Specifications of wall materials	Thickness (mm)	U-value
Thermal break	1	Single wall	12	5.7
	2	A double wall filled with air, space between the walls	12	3.4
	3	A double wall filled with argon, space between the walls	12	3.3
	4	Triple walls, the thickness of the walls	12	2.6
UPVC	1	Single wall	12	4.8
	2	A double wall filled with air, space between the walls	12	2.8
	3	A double wall filled with argon, space between the walls	12	2.7
	4	Triple walls, the thickness of the walls	12	2.1

color, and concrete are used for the ceiling, and white plaster, brick design, and gray color are used for the wall.

All the alternatives in the algorithm are defined as sliders for optimization, and the algorithm can choose the best options to optimize its three functional goals. In this study, the SPEA2 is used as an Octopus component in Grasshopper software for optimization. This algorithm optimizes thermal performance, lighting performance, and thermal comfort simultaneously.

The Pareto front responses analysis process

After the completion of the optimization process, the results, including the specifications of residential units and the amount of energy consumed, are extracted and collected. These data are subjected to descriptive statistics and analytical tests, including correlation and regression. According to Amrhein and Greenland [29], significance in correlation and regression tests is presented only as a report and cannot be cited for significance**.**

RESULTS

Based on the findings, the spatial configuration generator algorithm could generate about 4000 responses.

In order to reduce the computations among the responses based on experts' opinions and classification, the result set of 440 plans was separated and entered into the simulation and optimization process in the form of a slider. During the optimization process, settings are made based on background, which can be seen in the table. The final run process of the Octopus plugin has been performed for 72 hours on a laptop with determined specifications (Intel(R) Core(TM) i9-6500U CPU @ 2.50 GHz (4 CPUs), 2.5 GHz) with 32 GB RAM. Final optimization settings is reported in Table 5.

The 3D graph of optimization responses in Pareto front mode is shown in Figure 1.The optimization process has been carried out during 79 generations of simulation and about 4000 simulations of the optimization energy

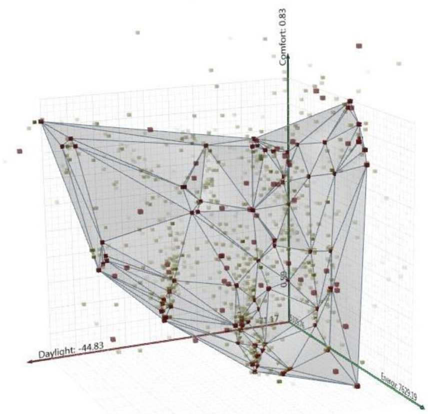
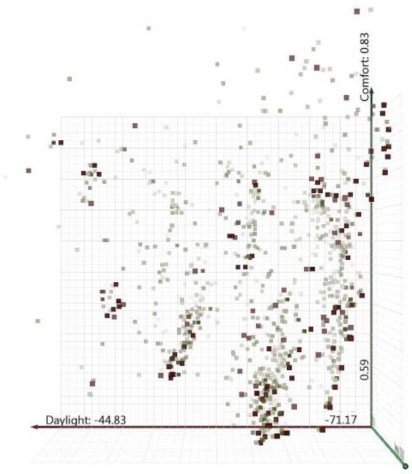


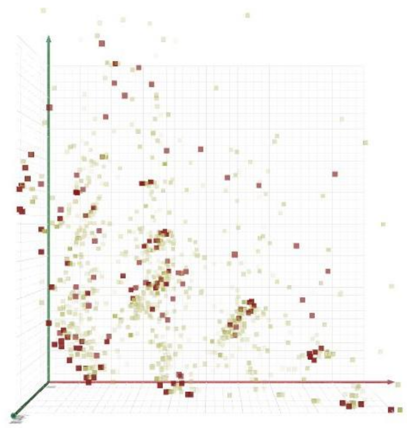
Figure 1. 3D graph of optimization responses in Pareto front mode

Table 5. Final optimization settings

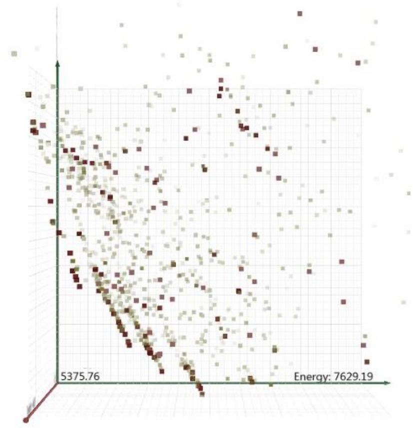
Crossover rate	Mutation rate	Elitism	Mutation probability	Population size
0.8	0.9	0.5	0.2	50



(a)



(b)



(c)

Figure 2. The final optimization responses in the Pareto front mode, (a) Side daylight-thermal comfort graph, (b) Top energy consumption-daylight illumination graph, (c) Front energy consumption- thermal comfort graph

performance. The final results can be seen on the Pareto Front graph.

With the presence of variables related to windows, shading, and materials, in addition to the variable of space configuration (variety of space layout), it was expected that the set of responses would lead to a limited number of specific spatial configurations. The reason for this is the great importance of these variables in the energy performance of the building due to their diverse solar reception. Figure 2 shows the final optimization responses in the Pareto front mode.

The 70 elite responses are determined in the Pareto front graph. In the meantime, after 79 generations of optimization, among the 440 configuration responses, only three configurations were seen among the 70 optimal responses. Also, among the best responses, there are only seven building orientations. Figure 3 shows the 2D graph of optimization responses in Pareto front mode.

The three responses obtained are with quasi-square, L-shaped, and quasi-rectangular structures. Among the selected space layout, plan code 0 among the 70 Pareto front responses, 62 cases with different conditions are repeated, which is the highest amount and shows that it is

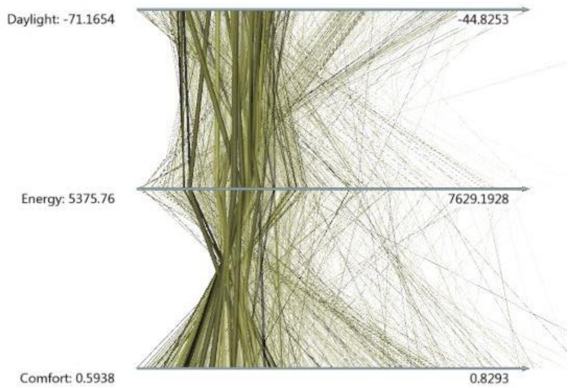


Figure 3. 2D graph of optimization responses in Pareto front mode

Table 6. Specification of the space layout of code 0

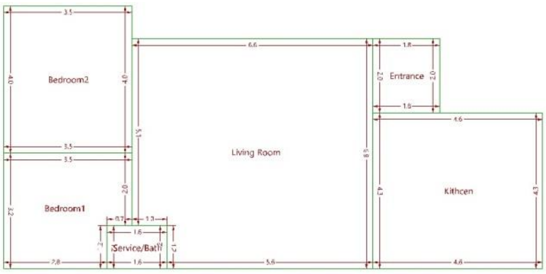
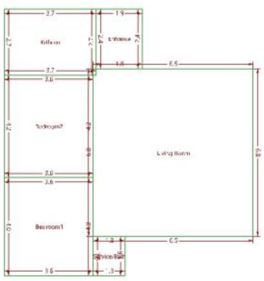
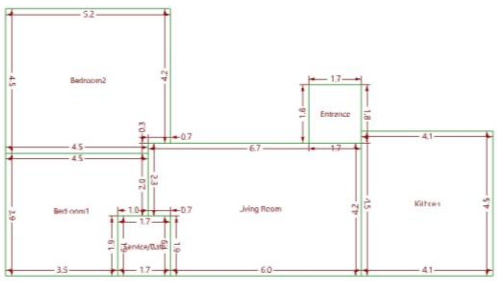
Optima space layout of Pareto front	Studied space	Dimensions (m)	Area (m^2)
Space layout: Code 0; 62 iterations			
	Reception	6.3* 6.6	40.5
	Kitchen	4.3* 4.5	19.35
	Parents' bedroom	3.5*4	14
	Children's bedroom	3.2 * 3.5	10.36
	WC and bathroom	1.6*1.2	1.92
	Entrance	1.8*2	3.6
Space layout: Code 406: 7 iterations			
	Reception	6.8*6.5	44.2
	Kitchen	2.7*3.7	9.99
	Parents' bedroom	3.5*4	14
	Children's bedroom	3.6*4	14.4
	WC and bathroom	1.3*1.4	1.82
	Entrance	1.9*2.4	4.56
Space layout: Code 15: 1 iteration			
	Reception	6.7*4.2	26.81
	Kitchen	4.1*4.5	18.45
	Parents' bedroom	4.2*5.2	21.63
	Children's bedroom	3.9*4.5	15.65
	WC and bathroom	1.7*1.9	3.23
	Entrance	1.7*1.8	3.06

Table 7. Frequency of orientation of plans among Pareto front responses based on space layout

Orientation	345	330	315	300	285	150	135	120	105
Plan code 0	42	8	1	9	2	0	0	0	0
Plan code 15	0	0	0	0	0	1	0	0	0
Plan code 406	0	0	0	0	0	0	1	4	2
Total frequency	42	8	1	9	2	1	1	4	2
Total frequency%	60	11.4	1.4	12.9	2.9	1.4	1.4	5.7	2.9

the most optimal response among the space layout of the algorithm. Table 6 summarized the specification of the space layout of code 0.

Among the Pareto front responses, nine orientation angles were obtained as optimal angles, the maximum of which belongs to the angle of 345 degrees. This angle appears 42 times among 70 responses. Figure 4 shows frequency of orientation of plans among Pareto front responses.

The angle of 345, or the angle of -15 degrees, reminds of the orientation of the straight room that the late Pirnia mentioned. The angle of 300 degrees with nine iterations and 330 degrees with eight iterations are among the popular angles of the algorithm. Frequency of orientation of plans among Pareto front responses based on space layout stated in Table 7.

Also, the height of the floor was optimized. Only two heights, g 2.7 and 3.1 m have been placed among the Pareto front responses. In the meantime, about 91% of the 70 elite responses have confirmed the height of 2.7m. Table 8 stated the frequency of floor height according to the variety of space layout among the Pareto front responses.

The height of the WC and bathroom space has been evaluated separately. In this study, the height of 2.7 m with a frequency of 46 cases has been assigned the highest amount. After that, a height of 2.5 m with a frequency of 14 cases is placed. Also, the results of the Pareto front in the materials of interior walls and flooring are presented in the Table 9.

In the following, the frequency of the area of the windows of the interior spaces in the Pareto front responses is presented in Table 10.

Also, regarding the type of windows used, among the eight options used in the algorithm, the frequency of each in the Pareto front responses are described in the Table 11. In the meantime, thermal break windows achieved better results.

The following specifications of the canopy, including the type, angle, and optimized materials, are evaluated. Among the Pareto front responses, the best canopy type, material, and angle are horizontal, metal, and 60 degrees, respectively. Table 12 stated the frequency of specifications in the plans among the Pareto front responses.

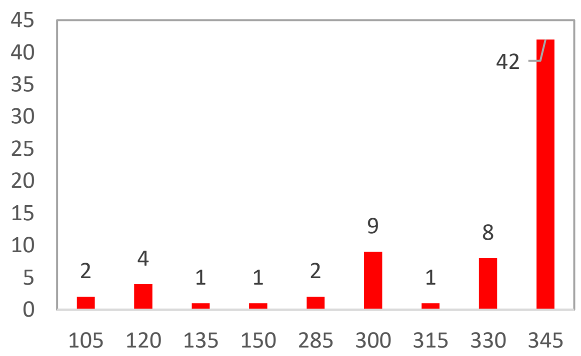


Figure 4. Frequency of orientation of plans among Pareto front responses

Table 8. Frequency of floor height according to the variety of space layout among the Pareto front responses

Floor height	3.5	3.3	3.1	2.9	2.7
Plan code 0	0	0	5	0	57
Plan code 15	0	0	0	0	1
Plan code 406	0	0	1	0	6
Total frequency	0	0	6	0	64
Total frequency %	0	0	8.57	0	91.43

Table 9. Frequency of materials among the Pareto front responses

Interior wall materials	Alternative 1	Alternative 2
Frequency	68	2
Frequency %	97.1	2.9

Flooring materials	Parquet, wood design	Brick design	Concrete
Frequency	48	22	0
Frequency %	68.6	31.4	0

Table 10. The frequency of the window area of the spaces in terms of the percentage of the space area among the responses of the Pareto front

Interior space	The area of windows as a percentage of the space area (%)									
	13	**18**	**23**	**28**	**33**	**38**	**43**	**48**	**53**	**58**
Children's bedroom										
Frequency	1	4	11	5	5	2	1	5	12	24
Frequency%	1.4	5.7	15.7	7.1	7.1	2.9	1.4	7.1	17.1	34.3
Parents' bedroom										
Frequency	15	2	6	8	28	3	3	2	2	1
Frequency%	21.4	2.9	8.6	11.4	40.0	4.3	4.3	2.9	2.9	1.4
Reception										
Frequency	-	-	-	-	1	2	20	5	8	34
Frequency%	-	-	-	-	1.429	2.8571	28.571	7.143	11.429	48.57
Kitchen										
Frequency	3	55	5	-	-	7	-	-	-	-
Frequency%	4.286	78.571	7.1429	-	-	10	-	-	-	-
WC and bathroom										
Frequency	1	1	27	3	2	2	1	33	-	-
Frequency%	1.42	1.42	38.5	4.28	2.85	2.85	1.42	47.14	-	-

Table 11. Frequencies of window type in plans among Pareto front responses

Window type	UPVC option 4	UPVC option 3	UPVC option 2	UPVC option 1	Thermal brick option 4	Thermal brick option 3	Thermal brick option 2	Thermal brick option 1
Frequency	1	4	0	4	5	22	23	11
Frequency%	1.4286	5.714	0	5.7143	7.143	31.429	32.857	15.71

Table 12. Frequency of specifications in the plans among the Pareto front responses

Canopy angle	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00
Frequency	5	17	12	3	6	16	6	2	3
Frequency%	7.143	24.28	17.14	4.28	8.57	22.86	8.57	2.85	4.28

Canopy materials	Brick	Wood	Metal	UPVC
Frequency	0	29	41	0
Frequency%	00	41.4	58.6	0

Canopy type	Vertical	Horizontal
Frequency	25	45
Frequency%	35.7	64.3

Also, it is necessary to check the results of three optimization performances among the responses. This study evaluated the descriptive statistics of daylight, thermal comfort index (PMV), and energy consumption. Table 13 presents the descriptive statistics of the results of three optimization performances.

The most daylight is related to a design with plan code 406, with an orientation of 105 degrees and a floor height of 3.1 m. In this plan, the canopy is vertical, and the canopy angle is 60 degrees. In this plan, the energy consumption is 6575.892 kWh, and the thermal comfort index is -0.823. The descriptive statistics of plans with minimum and maximum functional goals is listed in Table 14. Regarding daylight, the minimum was 44.06, and the maximum was 71.13 lux. The minimum daylight corresponds to a design with plan code 0, with an orientation of 345 degrees, with a height of 2.7 m. In this plan, the canopy is vertical, and the canopy angle is 30 degrees. Figure 5 shows the energy performance of responses 35 and 40 in the Pareto front.

The most daylight is related to a design with plan code 406, with an orientation of 105 degrees and a floor height of 1.3 m. In this plan, the canopy is vertical, and the canopy angle is 60 degrees. Figure 6 shows energy performance of responses 35 and 69 in the Pareto.

Also, the minimum and maximum thermal comfort index (PMV) among the responses of the Pareto border are -0.82 and 0.70. The lowest amount corresponds to the same plan with maximum daylight. The specifications of this plan are plan code 406, an orientation of 105 degrees, and a floor height of 3.1 m. The maximum thermal comfort corresponds to plan code 0, with a height of 2.7 m. Also, the orientation of the residential unit in this plan is 345 degrees with -15 degrees. Figure 7 shows energy performance of responses 39 and 1 in the Pareto front. Energy consumption among the Pareto front responses is also a minimum of 5375 and a maximum of 7629kWh. The minimum energy consumption is related to a design with plan code 0, with an orientation angle of 345 degrees and a height of 2.7 m. In this response, the vertical canopy is designed, and its angle is 30 degrees. The maximum energy consumption is related to a design with plan code 0, with an orientation angle of 285 degrees and a height of 1.3 m. The horizontal canopy is designed in this response, and its angle is 30 degrees.

DISCUSSION

This study has been carried out with a quantitative approach to build a generative model based on the placement of spaces, simulating and optimizing energy performance with the use of the target space of an apartment unit. The process of the generative space layout algorithm has led to the generation of diverse responses compared to similar studies [12] in terms of the overall shape of the plan. Compared to other studies with an area-based approach [10], the solution of this study used an innovative variable through the rectangle surrounded by the plan and the empty spaces between the plan and this rectangle. The specifications of the variable rectangle surrounded by the plan, along with the variable of the planning environment, among plans with equal area, can be favorable factors in evaluating the shape of the plan.

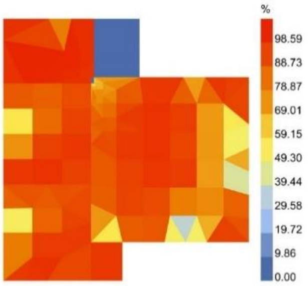
The variety of entrance layout responses to the optimization process in this study, compared to other studies, caused the results of the Pareto front to directly determine the orientation of factors affecting energy performance, thermal comfort, and daylight. In the Pareto front responses, the variety in factors such as orientation and space layout is low, and the variety in the specifications of windows and canopy is very .great In this study, after many investigations, the crossover rate of 0.8 and the mutation rate of 0.9 with the mutation

Table 13. Descriptive statistics of the results of three optimization performances

	N	Range	Minimum	Maximum	Mean		Std. Deviation	Variance
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic
Daylight	70	27.08	44.06	71.13	62.0109	0.82149	6.87309	47.239
PMV index	70	1.59	-0.82	0.77	-0.6669	0.02244	0.18778	0.035
Energy consumption	70	2253.43	5375.76	7629.19	6123.0834	59.08135	494.31005	244342.430
Valid N (listwise)	70							

Table 14. Descriptive statistics of plans with minimum and maximum functional goals

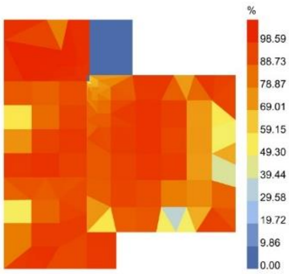
		layout plan	Orientation	Floor height	Ceiling materials	Wall materials	Elaborate work	The average area of the	Average length to the	Average window sill	Window type	Canopy type	Canopy angle	Canopy materials
Daylight	Minimum	0	345	2.7	4	1	2	3.75	0.375	1.05	2	Vertical	30	4
PMV index	Maximum	406	105	3.1	4	1	2	5	0.4	1.025	3	Vertical	60	3
Energy consumption	Minimum	406	105	3.1	4	1	2	5	0.4	1.025	3	Vertical	60	3
	Maximum	0	345	2.7	4	1	2	3.25	0.225	1.025	3	Horizontal	10	4
PMV index	Minimum	0	345	2.7	4	1	2	3.5	0.4	1.05	2	Vertical	30	4
	Maximum	0	285	3.1	4	1	1	6.75	0.55	0.975	8	Horizontal	30	3



Response 35, Pareto front
Maximum daylight among the responses
Energy consumption: 6575/892 kWh
Thermal comfort index (PMV): -0.823
Daylight: 71/134 lux
Layout plan 406
Orientation: 105 degrees

Response 40, Pareto front
Minimum daylight among the responses
Energy consumption: 5531/874 kWh
Thermal comfort index (PMV): -0.814
Daylight: 44/055 lux
Layout plan 0
Orientation: 345 degrees

Figure 5. Energy performance of responses 35 and 40 in the Pareto front



Response 35, Pareto front
Minimum thermal comfort among the responses
Energy consumption: 6575/892 kWh
Thermal comfort index (PMV): -0.823
Daylight: 71/134 lux
layout plan 406
Orientation: 105 degrees

Response 69, Pareto front
Maximum thermal comfort among the responses
Energy consumption: 5556/005 kWh
Thermal comfort index (PMV): -0.768
Daylight: 65/874 lux
layout plan 0
Orientation: 345 degrees

Figure 6. Energy performance of responses 35 and 69 in the Pareto front

Response 39, Pareto front
Minimum energy consumption among the responses
Energy consumption: 5375/759 kWh
Thermal comfort index (PMV): -0/809
Daylight: 44/809 lux
layout plan 0
Orientation: 345 degrees

Response 1, Pareto front
Maximum thermal comfort among the responses
Energy consumption: 7929/193 kWh
Thermal comfort index (PMV): 0/6015
Daylight: 65/47 lux
layout plan 0
Orientation: 345 degrees

Figure 7. Energy performance of responses 39 and 1 in the Pareto front

probability of 0.2 with a population size of 50 samples were evaluated as standard. Compared with the configuration generative design studies [13], the crossover and mutation rates have been higher. This issue is probably due to many algorithm architecture variables in this study. Also, the number of generations up to the Pareto front in this study was 79, which is a significant number compared to other studies [10]. The Pareto front's selected layout shows the rectangular shape's optimal performance with a 1 to 3 ratio among the three performance goals. The elongation of the form probably adjusts the type of solar gain in such a way as to provide a balance between the three variables of energy consumption, thermal comfort, and daylight. Also, the most optimal orientation mode is defined at an angle of 345 degrees, which is dominant among the Pareto front responses. This angle or angle of -15 degrees is exactly according to the straight room. This issue is a confirmation of the desirability of traditional Iranian architecture performance based on room classification. Angles of 30 and 60 are popular angles in the Pareto front responses.

CONCLUSION

Based on the research findings, it is confirmed that in Mashhad city, residential units with a rectangular shape with a ratio of 1 to 3 and square are the most optimal forms in terms of energy performance, thermal comfort, and daylight. Also, the best orientation angle is -15 degrees, following a straight room. Also, the optimal height for residential units is suggested to be 2/7 m. Based on Pareto front optimal responses, it is confirmed that spatial configuration optimization reduces energy consumption by more than 30% while providing thermal comfort to users. Also, in the daylight sector, more than 40% improvement is possible through optimizing the spatial configuration of the residential unit. The improvement of more than 30% in energy performance confirms that the design parameters affecting the configuration of the interior spaces of the building play a major role in the energy consumption and thermal comfort of the building.

According to the findings, it can be concluded that the generative algorithm designed in this study can generate the desired responses of the residential unit with high validity and reliability based on the design parameters of the configuration of the interior spaces of the building. Based on the final data of the Pareto front, it is confirmed that the SPEA2, in the form of the generative model coded in this study, was able to optimize the generated responses with high validity and reliability in terms of energy performance up to more than 30%. As it was said, the selection of steps in the optimization algorithm in this research has been done for two reasons, including reaching a comprehensive range of answers and an optimal number of configuration samples. In the future research, it is suggested to consider the optimization process with more limited steps based on the answers obtained in the Pareto front of this research

REFERENCES

1. Janda, K., 2009. Worldwide status of energy standards for buildings: a 2009 update, *Proceedings of the European Council for an Energy Efficient Economy (ECEEE) Summer Study*, pp. 1-6.
2. IEA – International Energy Agency, 2012. *World Energy Outlook 2012*. Accessed from ⟨http://www.worldenergyoutlook.org/publications/weo-2012/⟩ in May 2013.
3. Kanters, J., Horvat, M. and Dubois, M.-C., 2014. Tools and methods used by architects for solar design, *Energy and Buildings*, 68, pp. 721-731. Doi:10.1016/j.enbuild.2012.05.031
4. Attia, S., Gratia, E., De Herde, A. and Hensen, J. L., 2012. Simulation-based decision support tool for early stages of zero-energy building design, *Energy and Buildings*, 49, pp. 2-15. Doi:10.1016/j.enbuild.2012.01.028
5. Michalek, J., Choudhary, R. and Papalambros, P., 2002. Architectural layout design optimization, *Engineering Optimization*, 34(5), pp. 461-484. Doi:10.1080/03052150214016
6. Du, T., Jansen, S., Turrin, M. and van den Dobbelsteen, A., 2020. Effects of architectural space layouts on energy performance: A review, *Sustainability*, 12(5), pp. 1829. Doi:10.3390/su12051829
7. Ekici, B., Cubukcuoglu, C., Turrin, M. and Sariyildiz, I. S., 2019. Performative computational architecture using swarm and evolutionary optimisation: A review, *Building and Environment*, 147, pp. 356-371. Doi:10.1016/j.buildenv.2018.10.023
8. Rodrigues, E., Gaspar, A. R. and Gomes, Á., 2014. Automated approach for design generation and thermal assessment of alternative floor plans, *Energy and Buildings*, 81, pp. 170-181. Doi:10.1016/j.enbuild.2014.06.016
9. Wang, X.-Y., Yang, Y. and Zhang, K., 2018. Customization and generation of floor plans based on graph transformations, *Automation in Construction*, 94, pp. 405-416. Doi:10.1016/j.autcon.2018.07.017
10. Yi, H., 2016. User-driven automation for optimal thermal-zone layout during space programming phases, *Architectural Science Review*, 59(4), pp. 279-306. Doi:10.1080/00038628.2015.1021747
11. Sharpe, R., Marksjö, B., Mitchell, J. and Crawford, J., 1985. An interactive model for the layout of buildings, *Applied Mathematical Modelling*, 9(3), pp. 207-214. Doi:10.1016/0307-904X(85)90009-5
12. Rodrigues, E., Gaspar, A. R. and Gomes, Á., 2013. An evolutionary strategy enhanced with a local search technique for the space allocation problem in architecture, Part 1: Methodology, *Computer-Aided Design*, 45(5), pp. 887-897. Doi:10.1016/j.cad.2013.01.001
13. Dino, I. G. and Üçoluk, G., 2017. Multiobjective design optimization of building space layout, energy, and daylighting performance, *Journal of Computing in Civil Engineering*, 31(5), pp. 04017025. Doi:10.1061/(ASCE)CP.1943-5487.0000669
14. Pacheco, R., Ordóñez, J. and Martínez, G., 2012. Energy efficient design of building: A review, *Renewable and Sustainable Energy Reviews*, 16(6), pp. 3559-3573. Doi:10.1016/j.rser.2012.03.045
15. Gupta, R. and Ralegaonkar, R., 2004. Estimation of beam radiation for optimal orientation and shape decision of buildings in India, *Architectural Journal of Institution of Engineers India*, 85, pp. 27-32.
16. Plörer, D., Hammes, S., Hauer, M., van Karsbergen, V. and Pfluger, R., 2021. Control strategies for daylight and artificial lighting in office buildings—A bibliometrically assisted review, *Energies*, 14(13), pp. 3852. Doi:10.3390/en14133852
17. Amasyali, K. and El-Gohary, N. M., 2018. A review of data-driven building energy consumption prediction studies, *Renewable and Sustainable Energy Reviews*, 81, pp. 1192-1205. Doi:10.1016/j.rser.2017.04.095
18. Wang, L., Greenberg, S., Fiegel, J., Rubalcava, A., Earni, S., Pang, X., Yin, R., Woodworth, S. and Hernandez-Maldonado, J., 2013. Monitoring-based HVAC commissioning of an existing office building for energy efficiency, *Applied Energy*, 102, pp. 1382-1390. Doi:10.1016/j.apenergy.2012.09.005

19. Fernandez Bandera, C. and Ramos Ruiz, G., 2017. Towards a new generation of building envelope calibration, *Energies*, 10(12), pp. 2102. Doi:10.3390/en10122102

20. Zuhaib, S., Hajdukiewicz, M. and Goggins, J., 2019. Application of a staged automated calibration methodology to a partially-retrofitted university building energy model, *Journal of Building Engineering*, 26, pp. 100866. Doi:10.1016/j.jobe.2019.100866

21. Andrade-Cabrera, C., Burke, D., Turner, W. J. and Finn, D. P., 2017. Ensemble Calibration of lumped parameter retrofit building models using Particle Swarm Optimization, *Energy and Buildings*, 155, pp. 513-532. Doi:10.1016/j.enbuild.2017.09.035

22. Ferrara, M., Lisciandrello, C., Messina, A., Berta, M., Zhang, Y. and Fabrizio, E., 2020. Optimizing the transition between design and operation of ZEBs: Lessons learnt from the Solar Decathlon China 2018 SCUTxPoliTo prototype, *Energy and Buildings*, 213, pp. 109824. Doi:10.1016/j.enbuild.2020.109824

23. Carlon, E., Schwarz, M., Prada, A., Golicza, L., Verma, V. K., Baratieri, M., Gasparella, A., Haslinger, W. and Schmidl, C., 2016. On-site monitoring and dynamic simulation of a low energy house heated by a pellet boiler, *Energy and Buildings*, 116, pp. 296-306. Doi:10.1016/j.enbuild.2016.01.001

24. Li, W., Tian, Z., Lu, Y. and Fu, F., 2018. Stepwise calibration for residential building thermal performance model using hourly heat consumption data, *Energy and Buildings*, 181, pp. 10-25. Doi:10.1016/j.enbuild.2018.10.001

25. Trompoukis, X., Asouti, V., Kampolis, I. and Giannakoglou, K., 2012. CUDA implementation of Vertex-Centered, Finite Volume CFD methods on Unstructured Grids with Flow Control Applications, *GPU Computing Gems Jade Edition*: Elsevier, pp. 207-223. Doi:10.1016/B978-0-12-385963-1.00017-4

26. Zitzler, E., Laumanns, M. and Thiele, L., 2001. SPEA2: Improving the strength Pareto evolutionary algorithm, *TIK-report*, 103. Doi:10.3929/ethz-a-004284029

27. Salgueiro Sicilia, Y., Toro Pozo, J. L. and Bello Pérez, R., 2016. Evaluación del desempeño de la metaheurística MOVMO en funciones de prueba con restricciones, *Revista Cubana de Ciencias Informáticas*, 10(1), pp. 182-193. Available at: https://scielo.sld.cu/scielo.php?pid=S2227-18992016000100015&script=sci_arttext&tlng=en

28. Ghasemzadeh, M., 2012. Dimensional criteria and design considerations of urban residential unit spaces. Tehran, Iran: Road, Housing and Urban Development Research Center.

29. Amrhein, V., Greenland, S. and McShane, B., 2019. Scientists rise up against statistical significance, *Nature*, 567(7748), pp. 305-307.

Persian Abstract

چکیده

کلیه تصمیمات مهمی که بر عملکرد حرارتی ساختمان تاثیر می‌گذارند در همان مراحل اولیه طراحی اخذ می‌شوند. بر این مبنا، در این تحقیق مرحله اولیه طراحی معماری که مربوط به پلان فضایی است مورد هدف قرار گرفت. هدف این تحقیق رویکردی عالی برای ارزیابی و بهینه‌سازی انرژی مجموعه‌ای از راه‌حل‌های چیدمان فضایی جایگزین از طریق مدل طراحی محاسباتی عملکردی است. روش این تحقیق شامل ایجاد راه‌حل‌های منسجم طراحی و ارزیابی و بهینه‌سازی عملکرد انرژی راه‌حل‌های انتخابی می‌باشد. در بخش اول، تخصیص فضا در یک سطح، طرح را از طریق یک تکنیک تکاملی ایجاد می‌کند. در مرحله بعد، برنامه‌های خاصی از نظر عملکرد انرژی، رتبه عملکرد و بهینه‌سازی مورد ارزیابی قرار گرفت. ابزار شبیه‌سازی انرژی پلاگین‌های Honeybee و Ladybug است. ابزار بهینه‌سازی الگوریتم تکاملی Pareto در پلاگین Octopus است. میزان بازساخت، میزان دگرگونی و احتمال دگرگونی به ترتیب ۰/۹، ۰/۸ و ۰/۲ بود. نتایج نشان داد که هر الگوریتم ابزار مناسبی برای راه‌حل‌های طراحی، عملکرد حرارتی پلان‌های طبقه، کمک به دیدگاه معماران در فرآیند تصمیم‌گیری و سرعت بخشیدن به فرآیند طراحی است. در نهایت بر اساس بهینه‌سازی، نتیجه نهایی الگوریتم تحقیق ۷۰ پاسخ برگزیده در Pareto است. منتها در طول پاسخ‌های بهینه Pareto، مصرف انرژی می‌تواند بیش از ۳۰٪ در نور روز کاهش یابد و بیش از ۳۹ درصد بهبود حاصل شود.