Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2018 Volume 24 Issue 3: 193–205
https://doi.org/10.3846/jcem.2018.1678

COMPUTATIONAL OPTIMIZATION OF HOUSING COMPLEXES FORMS TO ENHANCE ENERGY EFFICIENCY

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Received 10 July 2017; accepted 22 March 2018

Abstract. This study aimed to consider the field of energy saving in architectural design utilizing computer analysis and calculation. In this analysis, architecture design with an approach to optimizing energy consumption in the design of individual units, complex plan sites, and apartment sets using a computer was studied. Parameters affecting this research include the geometry of units, the arrangement and location relationship of buildings, and the form and height of apartment units. Different plans were produced by utilizing the initial plan of the designer and changing some aspects of it approved by the architectural design using the parametric modeling technique. Utilizing similar logic and a shift in the arrangement of buildings on the site, a variety of options were produced. By selecting existing and pre-designed plans, the optimal form was produced by computer. After computer-simulating each option, the energy analysis process was started for each building design. In the optimization process for each of the three designs, a genetic algorithm was used to achieve the optimal solution. After accomplishing the various stages of optimization, the final option compared with the initial design had reductions in energy consumption of 21% in plan design, 2% in site plan design, and 26% in apartment units form design. It should be noted that the processes of simulation and optimization were performed in the context of a continuous algorithm and by utilizing parametric tools that reduced the duration of this process.

Keywords: algorithmic design, parametric modelling, optimization, energy saving, Grasshopper.

Introduction

Designing residential complexes while reducing energy consumption is a requirement the necessity of which is clear to everyone. After the energy crisis of the last century, many countries that have no fossil energy sources used systematic programs to better use different kinds of energy. Although the idea of using the best form of building by architects and urban planners goes back to 1960 (Olgyay 1963a; Martin 1967), this issue was not a priority for countries with large reserves of energy. In Iran (as the samples indicate), a building's average energy consumption is about 400 kWh per square meter, which is nearly 2.5 times the average global consumption. Moreover, household and commercial sectors account for nearly 39% of the country's total energy consumption and have become the biggest consumers of energy. Now, due to declining reserves and rising energy costs, there is an increasing tendency to optimize energy usage with various methods. For example, using passive solar design techniques in designing buildings is a most useful method.

Although there are specific strategies for dealing with climate problems, passive solar techniques sometimes produce conflicting responses. Some design properties are responsive to reducing energy consumption for both cold and warm seasons, although for details such as openings, shadings, etc., there are different strategies. A key issue in designing buildings in the Middle East is the problem of enjoying the winter solar radiation while maintaining a constant cooling energy in summer (Ghrab-Morcos 2005). For example, it is known that insulating a building helps reduce heating energy consumption. On many summer

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nights, however, outside temperatures are lower than inside temperatures, and uninsulated walls drain accumulated warmth at night leading to the reduced usage of cooling devices (Singh *et al.* 2007; Znouda *et al.* 2007). Apart from these problems inherent in passive methods, there may often be differences between good options from the perspective of energy and architectural design.

Clearly, the form of a building plays an important role in its energy consumption by significantly affecting the amount of its thermal energy storage and solar radiation absorption (Hachem *et al.* 2011a, 2011b). For example, a rectangular shape is generally considered an optimal shape for utilizing active techniques and reducing energy consumption (Chiras 2002). Despite the difficulties of access to light (Hachem *et al.* 2012), a rectangular plan may be inconsistent with design requirements. The same thing may happen when designing a set of buildings. Although the overall arrangement is an important factor in the total energy consumption of the set, the location and form of each building can seriously challenge the correct overall orientation. High-density plans reduce quantity, cost, and energy consumption while also reducing access to solar radiation (Steemers 2003). The general form of the site design and plan of the existing streets at the site can be determining factors in selecting building orientation and thus the amount of solar radiation received (Knowles 1981).

All the above-mentioned points emphasize the complexity of energy analysis and the interaction of adjacent units. Thus, the need to model different states of each option and investigate each factor is not only a time-consuming process, but, in some cases, an impossible issue that is even less possible using traditional modeling techniques. Therefore, the use of computer capabilities is proposed here; using a computer not only eliminates the frequent shuttle between architectural design software and similar climate simulation software, but also produces the best option by utilizing optimal finder techniques in response space.

The optimization method is very important. Due to the changes in domain of continuous operations, randomized optimization algorithms including GA (Genetic Algorithm) (Mossolly *et al.* 2009; Magnier, Haghighat 2010; Wright *et al.* 2002; Wang *et al.* 2005), PSO (Particle Swarm Optimization) (Ali *et al.* 2013; Djuric *et al.* 2007), and generative systems are often used to solve optimization problems, like building simulation models. However, achieving the optimal solution often requires hundreds or thousands of simulations using randomized algorithms. Much time, days and perhaps weeks, is needed to resolve simulation problems (Magnier, Haghighat 2010; Wang *et al.* 2005; Peippo *et al.* 1999; Nguyen *et al.* 2014). Of course, before optimization engines are applied in designing, the problems of two primary areas should be resolved: 1) providing a response space with the capability of functions development, and 2) adapting to a wide range of architectural scenarios (Eve Lin, Gerber 2014). Moreover, a successful methodology may lead to a reduction in energy consumption, dependent upon the selection of an appropriate technical strategy, which shows the desired reaction to specified factors in context (Hachem *et al.* 2012; Cellura *et al.* 2011). The relationship between climates of an appropriate form has been the subject of many articles and can be classified into four categories. The first deals with human thermal comfort as the base of designing with a passive solar approach (Olgyay 1963b; Givoni 1989, 1998). The second category deals with the issue of access to sunlight as a prerequisite for the use of the solar passive approach (Knowles 1981). The third focuses on the impact of urbanization with the correct climatology approach (Oke 1978; Okeil 2010). The fourth category, which is newer than the other three groups, is related to the discussion of automating the process of choosing the right approach in all three mentioned fields. The present paper can be grouped into the fourth area.

This article is part of a study in process. In addition to the effects of parameters involved in designing residential complexes, it addresses the energy consumption of different units in three general groups of the two-story villa plan, the form of a 12-story apartment building, and villa unit plan site and response optimization. Climate data from the city of Tehran, Iran was used in the study analyses.

1. Methodology and design approach

The research presented in this paper is divided into three main sections: 1) design of optimal plans for a two-story villa, 2) design of an optimal site plan for a seven two-story villas, and 3) design of an optimal forms for six 12-unit apartment building by fixed plan and certain locations in the designing site. For all three sections, the design option has been studied as a parametric search response. The design method for villas includes a basic plan as data and the capability of changing the angles, size, and arrangement of some plans in order to create different forms. With this feature, infinite options can be created from the main wishes of the designer which are transferred to the computer by the initial plan. Designing the site plan of villa units is the next phase of the research and is created using the optimized version of the plan from the previous step. At this stage, 8 similar villa units are simulated, each open to location change within the designing site. The computer can create quite different plans by changing the location of all 8 buildings. The third area of research is related to the change in form of apartment buildings. Although all 6 apartments use the 4-story, 12-unit plan, several d forms can be created by changing the number of stories in each part of the apartment building. All simulated sites were assessed using DIVA simulation software that analyzes with the Energy Plus-fit engine (Graduate School of Design at Harvard University 2014). After energy consumption is determined using genetic algorithms, the sites enter the optimization cycle. Three factors give this technique a significant advantage over traditional methods: 1) details of plan modeling are replaced by physical data as raw parameter data (input); 2) computation is faster and plans are corrected more easily; and 3) various plan alternatives are available for immediate use (Lin *et al.* 2013).

1.1. Villa units: specifications and parameters

Due to plan changes generated by the computer, each villa unit floor ranged between 140 and 160 square meters in area by using 3 rotational parts (living room and two bedrooms) which are added to the fixed parts of plan and was 3 meters in height. The idea is that the computer must use initial design of architects and develop architects design in the limited items define by them by evaluating lots of similar moods that is not possible for architects. Further explanations are provided in sections 5.1.1 and 5.1.2 of present article. Prototypes were made to begin the optimization process. Some computer-generated forms are shown in Figure 1. As indicated in Figure 1, computers are capable of changing the parametric angles of elements to create new plans.

1.2. Apartment units: specifications and parameters

The apartment buildings have 4 connected units, with unit A measuring 158 m^2, unit B measuring 55 m^2, unit C measuring 55 m^2, and unit D measuring 167 m^2. The computer is supposed to use the given plans to create different forms, but it also has the option of changing the number of floors used from each apartment building plan and producing various forms. The locations of the apartment buildings are specified and fixed in the design site. For comparison, details used in both apartment and villa units are listed in Table 1.

Table 1. Main character of building simulation

0.04 people/m^2	(Number of people)/m^2 floor area
11.74 W/m^2	Lighting load
2.7 W/m^2	Equipment load
C18- C26	Comfortable zone
0.5	Infiltration Rate (air changes per hour)
0.001 ((m^3/s)/people)	Fresh Air

1.3. Site plans, specifications and parameters

The issues of shadowing and apartment buildings overlooking villa units are important issues in Iranian architecture. The plan site was divided into two main areas. As evident in Figure 2, 7 villa units were placed in the southern, smaller part, and 6 apartment buildings were situated in the northern, larger part. Without regard to the climate, the northern part was designed geometrically with the maximum distance between buildings, but

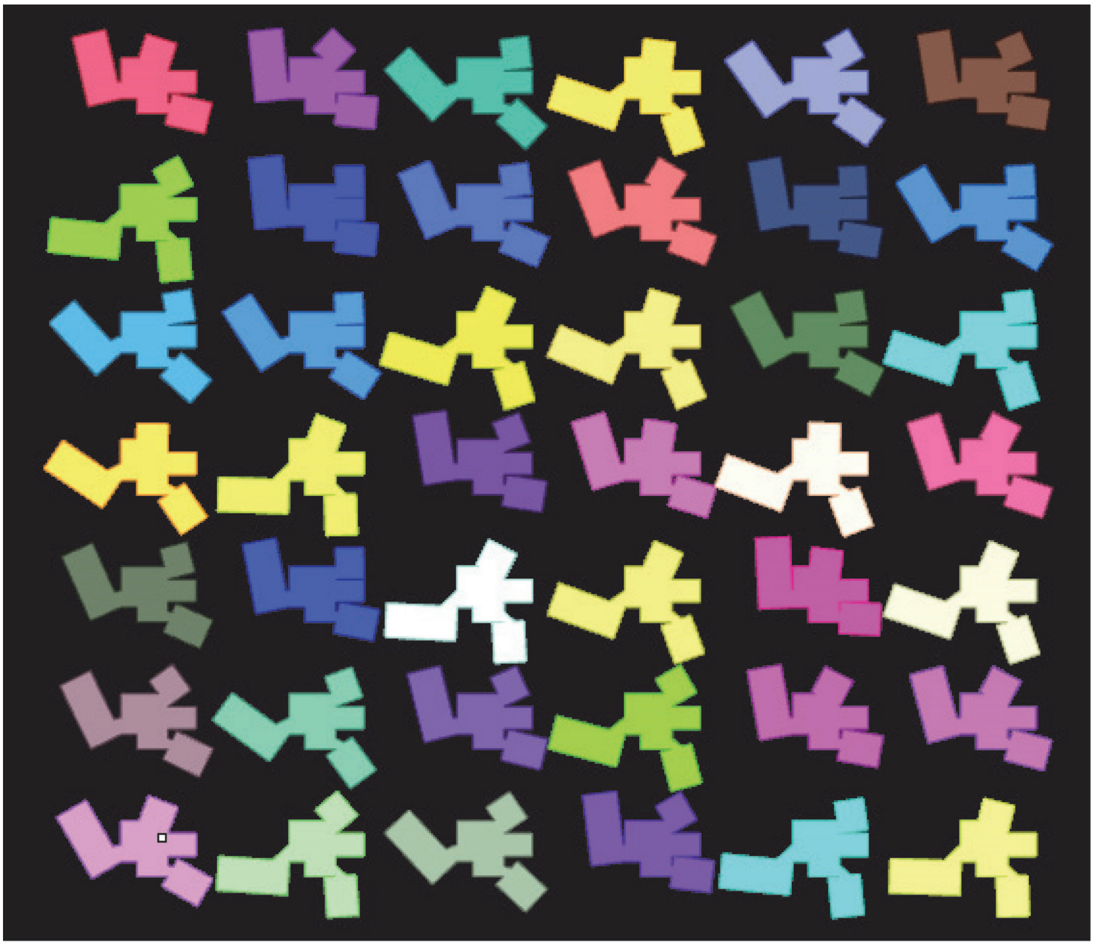


Figure 1. Some of generated parametric plans by algorithm

Figure 2. Site plan of complex

building placement for the southern side of the villa units was determined from the countless computer-generated options which were assessed and with reducing energy consumption in mind, the final option was then selected.

1.4. Simulation modelling

Energy Plus Building energy simulation software was used in this study as an engine analyst. Rhinoceros software was used as the graphical environment and displayer of response, and the Grasshopper plugin was used as an interface environment to create real time communication between the two programs and the optimization of responses. Every single building was considered a single-conditioned zone, and a four time steps per hour was used in the simulations. The main characteristics of the models used in the analysis by Energy-Plus software are briefly described below.

1.4.1. Weather data

This study was applied in Tehran, Iran, (35 ^ N latitude). Tehran's climate is hot and dry in summer and mild and sometimes cold in winter. The highest recorded temperature is about 42.5 °C, the minimum is –20.5 °C, and annual average temperature is about 16.5 °C (The weather network 2014). Analyses of heating energy consumption and cooling energy consumption calculations and optimization were performed in a time period of one-year. Energy Plus weather data files, which simulate building energy calculations for a one-year period, were used for simulations. The information included hourly values for solar radiation, ambient temperature, wind speed, wet bulb temperature, wind direction, and cloud cover extrusion (Hachem *et al.* 2012).

1.4.2. Energy Plus solar radiation computations

Moment sunshine was used for the calculation of not only direct beam and diffuse radiation, but also radiation reflected from the ground or other lateral surfaces. The solar model used in this study was the ASHRAE clear sky model (ASHRAE 2005). Validation tests showed that the simulation code used in Energy Plus was suitable and highly accurate for calculating the total amount of solar energy radiated on the building view by long-term analysis (Loutzenhiser *et al.* 2007). Heat flow through windows showed that Energy Plus calculations differe only 5.8 from the experimental data (Loutzenhiser *et al.* 2009).

1.5. Genetic algorithm

Genetic algorithms are a subset of evolutionary algorithms (EA) that work with a similar approach to search and find the optimal response to a specific issue. A genetic algorithm consists of two parts: options and evaluation. The following actions take place in the process of an algorithm: (1) the initial population of options is produced, (2) the compatibility of options with favorable conditions is assessed, and (3) the cycle is repeated until the cessation of operations (time limit reached or desired level of compatibility achieved). (1) The options for reproduction are chosen; (2) new options are bred and produced (using techniques such as changing, interactions, etc.); (3) the compatibility of new alternatives with favorable conditions is evaluated; (4) undesirable options are replaced by desired produced options (Khabazi 2012). Genetic algorithms are based on the theory of natural evolution. In optimizing using these algorithms, the population of candidate solutions for a problem is measured. Each of these options has a fitness value that specifies the amount of its appropriateness in the response space (Yang *et al.* 2014). Although increasing the number of these generations usually leads to a more efficient answer, it also increases computing time. Without changing the specifications of the computer processor, there are two main ways to reduce computing time:

1) Reduce population size or the generation number of GA (Ali *et al.* 2013);
2) Apply simplified modeling or alternate models instead of complex and detailed modeling (Magnier, Haghighat 2010; Peippo *et al.* 1999).

In the issue mentioned in this paper, genetic algorithms optimized operations by changing the shape, arrangement, and form of buildings and measuring the required energy consumption per kilo watts per square meter.

2. Modeling and analyzing algorithms

2.1. Three-dimensional modeling algorithm

The first step in analyzing a building's energy use is to correctly simulate and provide detailed information on the factors that make up the building. It should be noted that simulating a building to analyze and compute the amount of energy it consumes is fundamentally different than simulating a building for its appearance features or presentation. In this study, the authors produced an algorithm in the Grasshopper, a plug-in for Rhino software, which has the capability of producing a presentable model for climatic simulation by receiving initial information related to a building (Figure 3).

The use of algorithmic modeling, allows designers to significantly reduce modelling time, which is an important

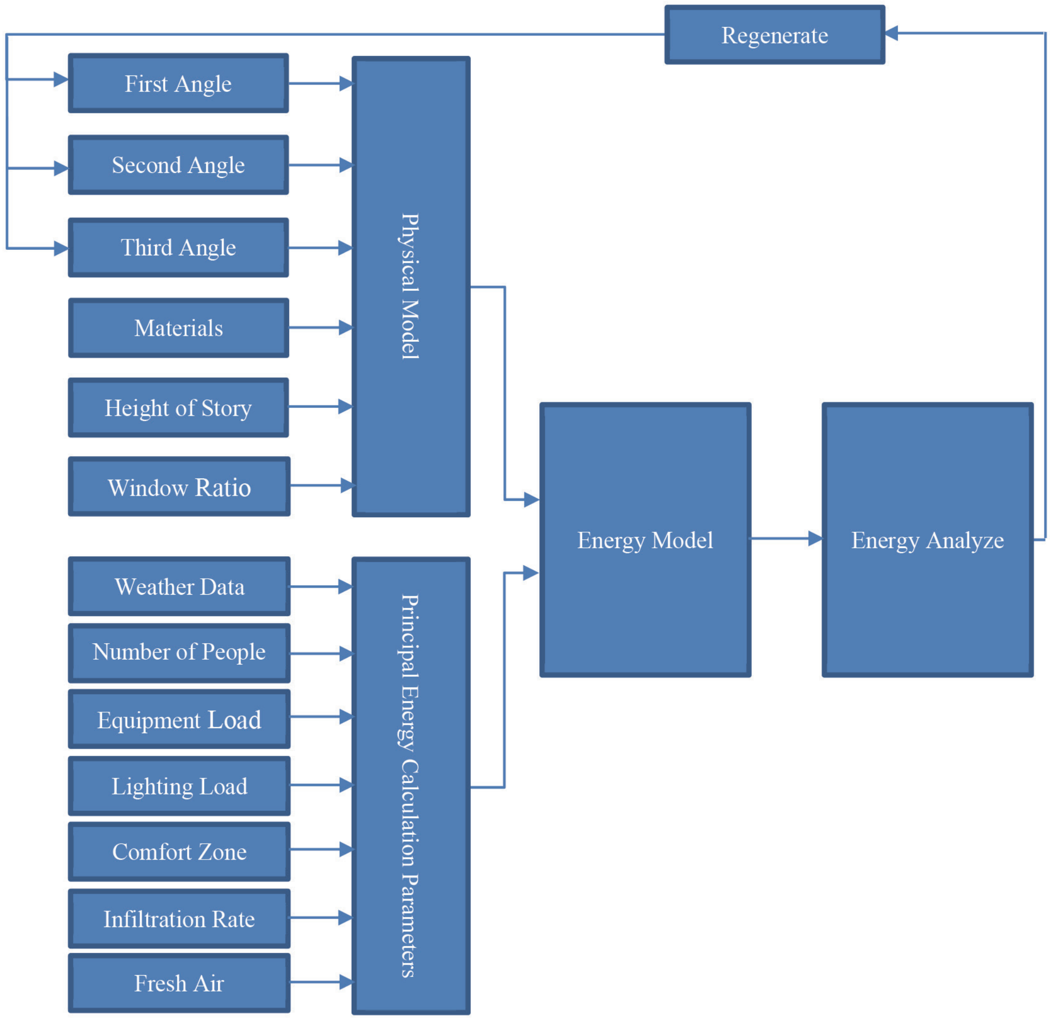


Figure 3. The algorithm process for villa's modeling and simulation

part of performing an energy analysis. Moreover, the advantage of obtaining parametric tools in simulating facilitates the application of changes to the model and the analysis process. Low computing load in modeling provides the possibility of a lot of analyses in a short time.

2.2. Algorithm of energy simulation

After modeling the building and providing information related to materials and climate to the computer, the analyzer algorithm starts the climate calculations. This algorithm uses the engine of Energy Plus software. Energy simulation algorithms are not in the scope of this paper and for more information about the engine of Energy Plus and its algorithm read. Form, function, and time of analysis as well as weather information are the factors determined in this algorithm.

2.3. Algorithm of optimizing energy

Previously, finding optimal solutions entailed repeated analysis and repeated trips between the simulator environment and the analyser software. Since a large part of the simulation should be repeated, it was considered too costly and burdensome. Now, however, finding optimal solutions has been made easy through the use of the parametric tools algorithm. The process of response optimization is performed using evolutionary algorithms and genetic algorithm techniques. The optimization algorithm gives one the ability to eliminate frequent and sometimes unproductive trips between the simulation and analyzer, find the optimal response through a large number of analyses and low response time, and provide it to the architectural designer. Optimization in this study was conducted in three separate areas. First, the optimal solution for plan design was found by changing the component angles in the original plan. Secondly, optimized plan sites for seven villa units were provided. Third, an optimized form for 12-unit apartment buildings was created. It should be noted that to optimize each of the three parts listed, depending on the complexity and time required for every analysis, a number of different generations and the different number of genes in each generation of the optimization process were used. They are shown in Table 2.

Table 2. Optimization algorithm's properties

	Max. stagnant	Population	Initial boost
Plan	30	30	2
Site plan	20	20	2
Form	15	20	2

3. Optimization genome, fitness and its results

3.1. Plan optimization

3.1.1. Governing GA genome and fitness

Plans vary according to the area generated by the algorithm. Optimal assessment should compare the energy consumption per square meter structure achieved. Plans generated in this study can be productive through three main angles are known. Each villa has 3 different joints in its plan. Although Villa's entrance and its kitchen are fixed, living room and two bedrooms can be rotated by 90 degrees from their attachment points to configure different shapes of plans. So the possible moods of the plan are equal to 90^3 (729000). The genetic algorithm must find the best shape of the plan by comparing total heating and cooling consumption in each, divided by their area (fitness). After optimization, the best choice is found. Table 3 shows the results of the top 10 states with plans consumption per square meter, area, and perimeter of the show. Figure 1, obtained by analyzing the data in Table 3, indicates a linear relationship between increased consumption and increased environment to surface of plans in Figure 4.

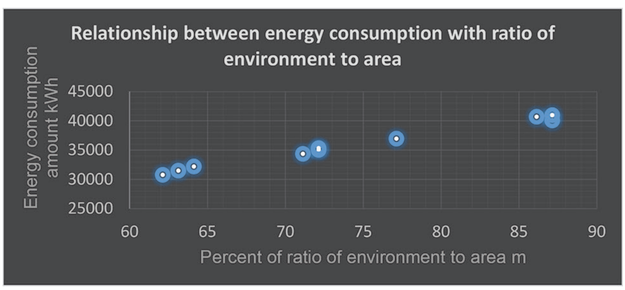


Figure 4. Relationship between Energy Consumption with Ratio of Circumference to Area

3.1.2. Plan optimization result

The results of plan optimization operations were acquired using genetic algorithms and measuring 30 different modes of the plan in every step of optimization during 30 steps. During this process, a final option was provided, that compared with the first option, required 21% less energy to provide the human comfort range (Figure 5).

3.2. Optimization of site plan

3.2.1. Governing GA genome and fitness

The location of buildings in relation to one another as well as to the site considered for designing are important issues affecting the amount of energy consumed in buildings. Although it can be accepted as a premise that the combination and integration of two or more separate buildings in a single volume often have a positive response, the existence of different modes, achieving different options, and finding the optimal design state is feasible only with careful measuring and value comparison of each. Therefore, as an integral part of site designing, the relationship between arrangement and location of villa buildings in the southern part of the design and energy consumption was measured and then optimized. For locating villas in the site plan, 2 parameters are used per unit. The parameters define X and Y features of units' centers. The most crucial issue is that these 7 units should not collide with each other or pick the same position. To avoid these problems, one positive number must be added to the energy calculation results as a penalty of villas collision, which is related to the collision area (positioning penalty is equal to 10000*collision area). Because of locating 7 villas, 14 numbers are defined as the parameters and the total amount of heating and cooling consumption is considered as the genetic algorithm fitness (Figure 6).

3.2.2. Results of optimization of plan site

The result of this process is summarized in Table 4. In accordance with the results, energy consumption in the final choice was reduced by 2% compared with the input option. It should be noted that to prevent interference of buildings that reduces the calculated energy consumption, negative scores were considered per square meter of in-

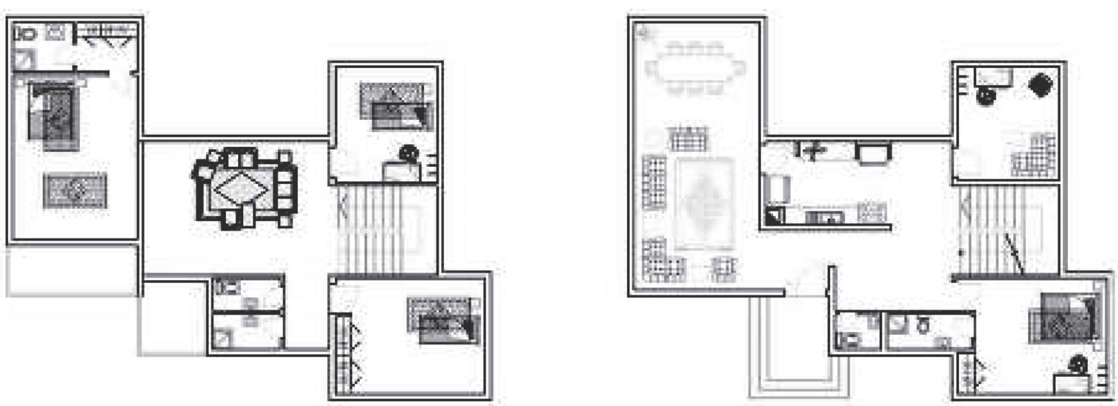


Figure 5. Final plan presented by algorithm

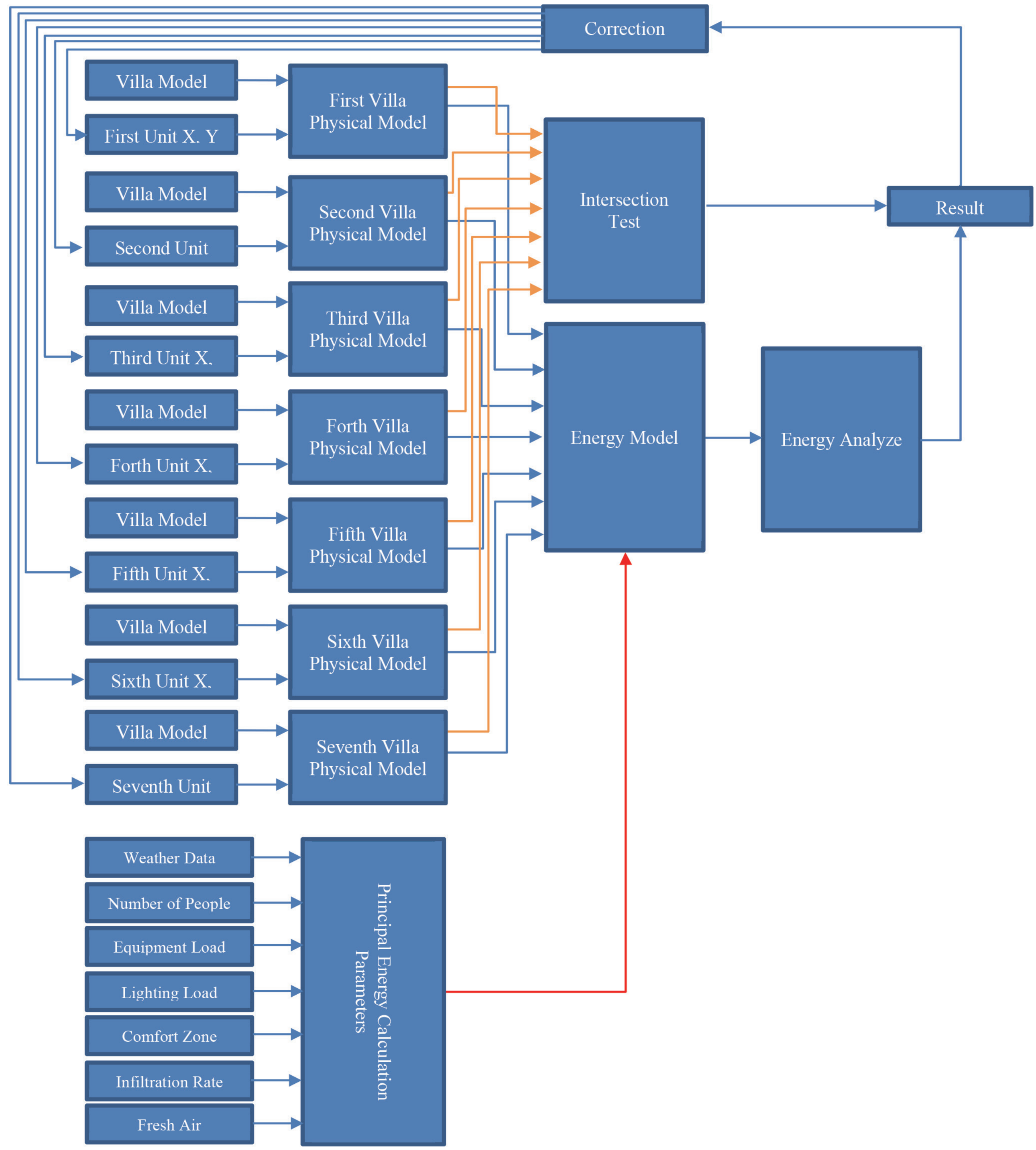


Figure 6. The algorithm process for site plan modeling and energy simulation

tervention for both cross buildings. Overlapping options are investigated, but their interference is reduced as much as possible.

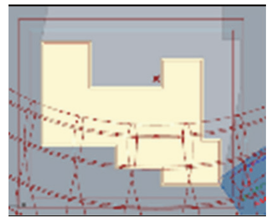
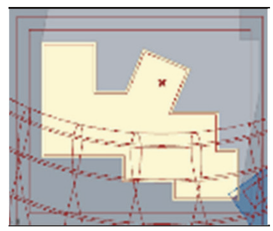
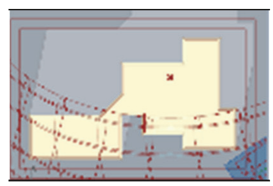
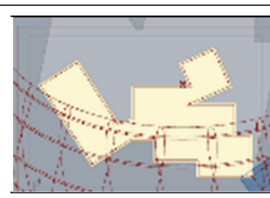
Results of optimizing the site plan were achieved using genetic algorithms and measuring 20 different arrangements of 7 plans of villa units at any stage of optimization and during the 20 stages (400 moods). During this process, the final option provided, compared to the initial option, needed 2% less energy to provide the human comfort range (Figure 7).

3.3. Form finding of the apartments

3.3.1. Governing genome and fitness

After different concepts of designing apartments were applied to the initial plans, another algorithm was written and used to choose the best option in terms of reducing energy consumption (Figure 8). The result of studies required the design and construction of 6 apartment buildings with 12 units and a maximum of 6 floors foe each. Each story of the buildings can be consists of 4 dif-

Table 3. Best optimized options in a one year span

	Used angel	Plan form	Annual energy consumption	Consumption per square meter	Area of plan	Perimeter of plan
1	30759 kWh	234 kWh/m^2	134 m^2	63 m		0,0,0
2	31473 kWh	242 kWh/m^2	127 m^2	62 m		90,0,0
3	32187 kWh	246 kWh/m^2	130 m^2	64 m		67,0,0
4	35027 kWh	256 kWh/m^2	137 m^2	72 m		0,90,0
5	35312 kWh	261 kWh/m^2	135 m^2	72 m		0,0,90
6	34338 kWh	265 kWh/m^2	129 m^2	71 m		90,90,0
7	36934 kWh	273 kWh/m^2	134 m^2	77 m		24,33,0

End of Table 3

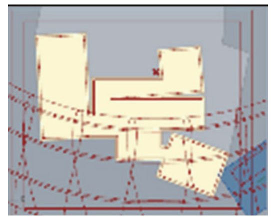
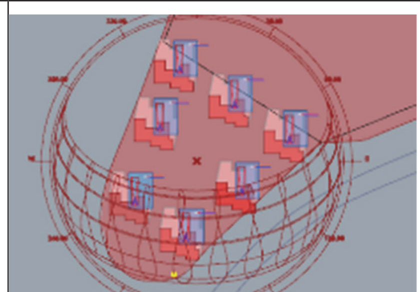
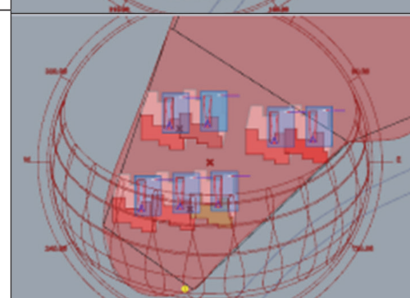
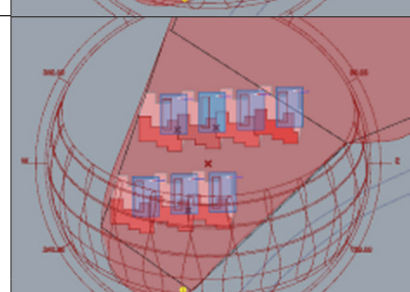
	Used angel	Plan form	Annual energy consumption	Consumption per square meter	Area of plan	Perimeter of plan
8	40041 kWh	297 kWh/m^2	134 m^2	87 m		5,3,20
9	40674 kWh	299 kWh/m^2	135 m^2	86 m		90,90,50
10	40952 kWh	302 kWh/m^2	135 m^2	87 m		45,45,45

Table 4. Some of generated site plan by algorithm

The period of analysis	The total amount of heating and cooling energy consumption	Arrangement of apartment site
Annual	228099 kWh	
Annual	225767.92 kWh	
Annual	225807.31 kWh	

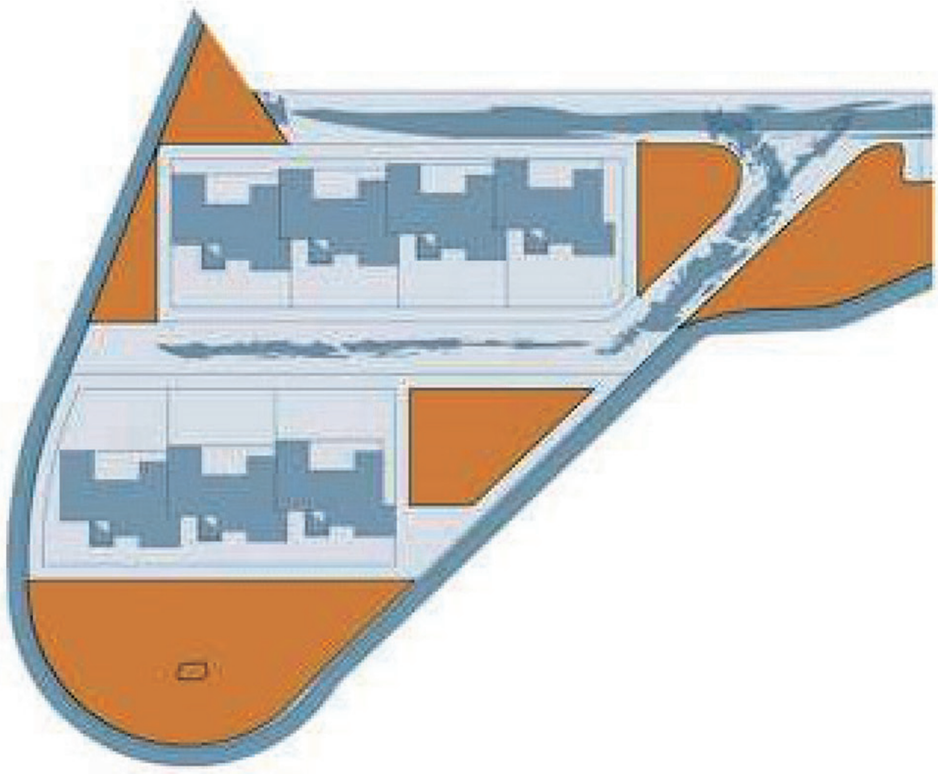


Figure 7. Final villa site plan alternative presented by algorithm

ferent types of apartment units. 4 numbers per building, demonstrate the number of each apartment unit type to configure the different building stories and form (24 parameters in whole complex). These 24 parameters can provide about 8.9 * 10^15 different possible alternatives. The major point is that buildings shadow can alter heating and cooling consumption of apartment complex. To have a better consideration of this issue, in the energy calculation process of each building, the shading buildings are added to the energy model as shading objects. So in each apartment building complex mode, the calculation must evaluate 6 different building energy consumption calculations of which each holds 5 buildings as shades. The whole amount of all heating and cooling consumption of 6 buildings is defined as the genetic algorithm fitness. After analysis and evaluation of various moods, the computer provided the designer with a combination of 12 units with optimum energy usage as the final product. Analysis of the top ten results and the constituent parameters are shown in Table 5.

3.3.2. Results of optimization of form finding the apartments

Results of optimizing apartment units were achieved using genetic algorithms and measuring 20 different forms of 7 apartment units at any stage of optimization and during

Table 5. Results of the best generated apartment forms by algorithm

The total amount of heating and cooling energy consumption	Number of western floors	Number of eastern floors	Number of northern floors	Number of southern floors
134879 kWh	4	4	3	1
134997 kWh	3	3	4	2
138140 kWh	4	4	1	3
138145 kWh	5	5	1	1
138517 kWh	3	4	3	2
138700 kWh	4	4	2	2
138747 kWh	3	4	4	1
138859 kWh	3	5	3	1
139530 kWh	3	4	2	3
140062 kWh	5	4	2	1

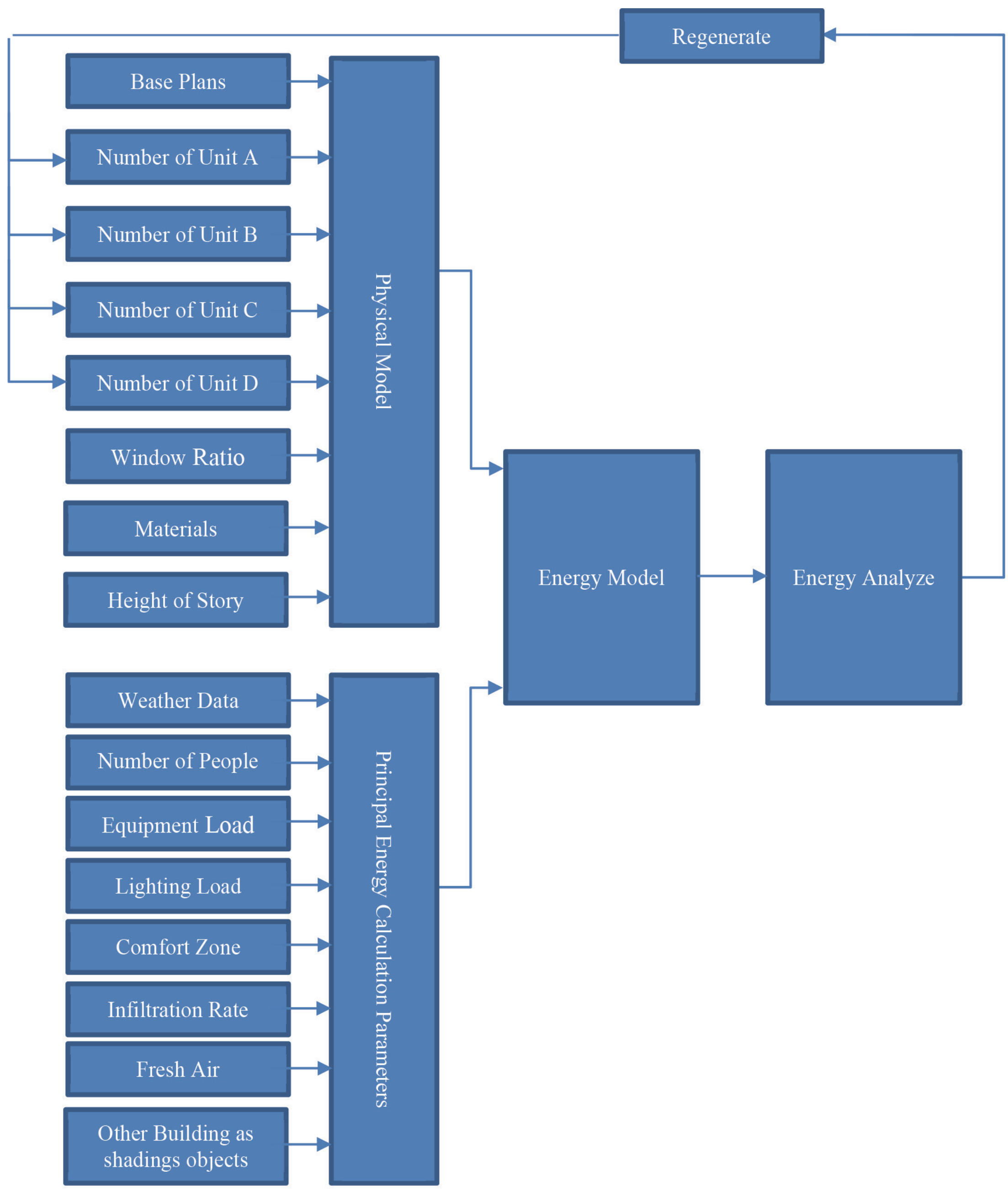


Figure 8. The algorithm process for one of the apartment building modeling and energy simulation. In this process the other building must added as shading objects. And this process must be repeated for each apartment building

the 15 stages. During this process, the final option provided, compared to the initial option, needed 26% less energy to provide the human comfort range (Figures 9 and 10).

Conclusions

The field of using digital tools in architectural design has made significant progress in recent times and is no longer limited to drawing processes and secondary issues of designing. This partnership has led to new horizons that were previously impossible to imagine because of their complexity.

Computer tools can be used to design different aspects of projects. The computer, especially in removing and making intelligent the processes of reciprocation between environments of design and analysis software, is effective. It is so effective, in fact, that in addition to finding more optimal and accurate responses, they reduce the time of these processes significantly. The research conducted using digital devices intended to provide options to designing with a parametric approach which, by using the power of computing as well as preserving a degree of the architectural designer's participation through intervention in functional algorithms and changing variables affecting the

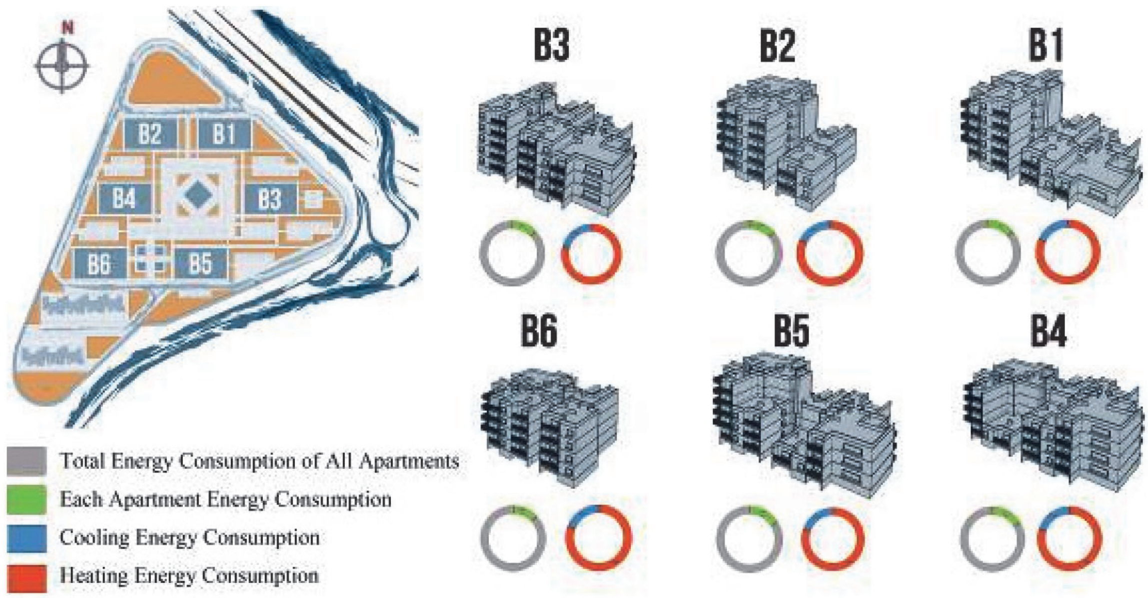


Figure 9. Final forms of apartment buildings to optimum energy efficiency

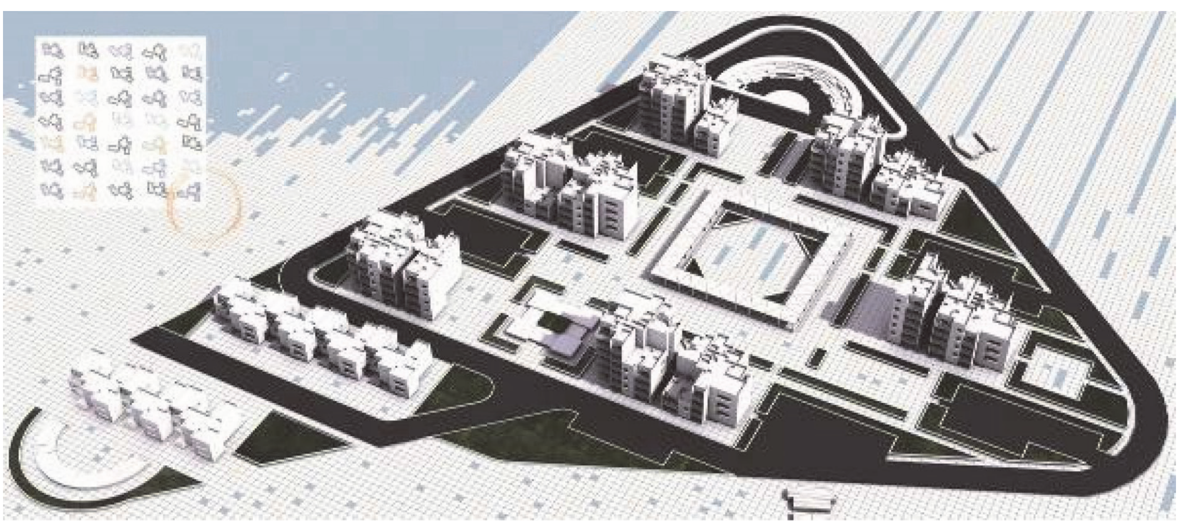


Figure 10. Final result of complex design by algorithm

response environment, produces optimal options in terms of energy consumption.

This field of research began with the contribution of digital tools to the design of plan. The current study addresses designing forms of apartments and placing them in the designing domain; that were optimized with values of 21%, 2%, and 26%, respectively, compared with the initial options that were designed to reduce energy consumption, but without using optimizer tools.

Generally, the advantages of proposed method in comparison to the classical methods are listed below:

1. Creating parametric modelling and generating all possible results in the short period of time.
2. Dispensability of modelling in secondary energy calculation software such as Energy Plus, Ecotect, and Design Builder.
3. Obviation of back and forth process in order to elimination of detected faults based on the different energy software data.
4. Optimization in order to finding the best or one of the best possible scenarios without using secondary optimization software such as MATLAB.
5. Optimization in order to reach to the best or one of the best possible scenarios of the whole elements' complex in its composition.
6. Independency from energy experts in order to make serpentine energy model.
7. Independency from software experts in order to do optimization process.
8. Creating the vast spectrum of proper results to gain clients' satisfaction.

9. The possibility of simultaneously developing different strategies or different results up to the final level of design by computer aided architectural design process.

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