BUILDING FOOTPRINT OPTIMIZATION FOR TWO IRANIAN CITIES VIA GENETIC ALGORITHM APPLICATION

S.M Lajevardi[1], M.H Saidi[1], M. Anooshahpour[2]

[1]School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran
[2]Department of Computer Engineering, Sharif University of Technology, Tehran, Iran

ABSTRACT

A genetic algorithm (GA) is an optimization means for green building design that has often been applied to 'green' designs. In this study, we concentrate on the optimization of building footprints with a multi-objective GA (MOGA). The GA is employed to generate feasible solutions simulated in terms of thermal behaviour, using the DOE2.2 as a detailed thermal analysis program. The simulation's results are then used to guide the GA search towards optimal trade-offs between reductions in energy consumption, during building operation, and the size of building perimeter for reducing the initial cost of material.

The case-study involves three 1000m^2 polygonal-shaped (quadrilateral, pentagonal and hexagonal) areas, as standard office buildings, located within two climatically-different Iranian cities, North Tehran and Bushehr. The MOGA results demonstrate that there exists significant difference amongst the optimal shapes and perimeter sizes - between the two climates – investigated in our study.

INTRODUCTION

High energy consumption, in buildings, constitutes one of the most important problems within developing countries that can both influence the economy and the environment. Every year, approximately 150,000-200,000 new residential buildings are constructed in Iran. Hence this critical study aims to guide designers and policy-makers to establish better decision-making during early design stages.

The best opportunities for integrating green design strategies occur at the conceptual design stage. During this stage, many potential design alternatives are generated and their performances are semi-evaluated in order to opt for the most promising solutions. The building shape is one of the most crucial considerations within the conceptual stage of building design. Since the building configuration determines the size and orientation of the exterior envelope, exposed to the outdoor environment, it can affect building performance in many aspects, namely energy efficiency, cost and aesthetics. Too often, however, decisions on the building shape are based on aesthetics alone, which notably leads to limiting the potential for performance improvement. Shape optimization can assist overcome this disadvantage by exploring more design alternatives, at the conceptual design stage, for specific criteria such as environmental and economical performance (Wang et al. 2006).

A basic principle of green building design is to lower or minimize the negative impacts on the already built environment, while taking cost and other performance criteria into consideration. This principle is implemented in previous studies via four methods: the empirical rule or guideline-based manual method, the simulation-based trial-and-error method, the knowledge-based method and the optimization method. The optimization method aims at finding optimal solutions with respect to some predefined performance criterion. In essence, optimization is an automated process incorporating three steps: generation, simulation and evaluation (Wang, 2005).

GA is an optimization method that has been applied to many types of building-associated optimization problems. Caldas and Norford (2003) have exercised two objectives GA whereby optimal trade-offs between energy consumption reduction, during building operation, and initial costs due to construction material were evaluated. Wang, Rivard, and Zmeureanu(2005, 2006) have optimized several different configurations including: the quadrilateral shape, the L-shape and the pentagonal shape for typical office buildings, by means of two objective GA, acquiring optimal trade-offs between a reduction in the life-cycle's environmental impact and cost. Concerning the former (optimization of pentagonal floor shapes), Wang et al had implemented a shape representation algorithm that we, too, have employed in our study. They introduced three types of shape representation – length-angle, length-bearing and Cartesian representations – and used the former two in their study. They concluded that the length-bearing representation produces better performance results in computation.

This paper aims to analyze whether the integration of architectural design within generative systems optimizes building footprints across different weather climates.

OBJECTIVE

Some countries like Iran behold a wide spectrum of diverse weather conditions. All too often, one notes that the building designs within these countries are usually quadrilateral. Our investigation had planned to ascertain whether other configurations, for future buildings, would prove to be more energy/cost-effective.

We implemented a two objective GA and a length-bearing representation in order to attain optimization within several polygonal buildings (quadrilateral, pentagonal and hexagonal) within two different weather conditions (those of North Tehran and Bushehr) in order to compare their shapes vis-a-vis energy consumption and perimeter size.

The general trend yielded is that the perimeter increases in accordance with the life-cycle cost (Wang et al. 2006). Since the studied buildings have a fixed floor area and height, the perimeter can be a good criterion au lieu de life-cycle cost; the latter requiring much time computation-wise and can, in turn, be employed as a valuable indicator to measure the compactness of a building.

SIMULATION

Some research studies have been carried out vis-à-vis the accuracy of simulation tools. For example, a different approach was developed and applied by Yezioro, Dong and Leite (2007) in relation to simulation tools. An inverse data model was developed using the artificial neural network method [ANN]. This model has been used as the base model for the validation and evaluation of heating and cooling electricity consumption for all simulation tools used in this study. Yezioro et al's studies demonstrated that eQUEST accommodated well to the inverse model in terms of total annual energy consumption and heat and cooling annual consumption.

eQuest is a relatively easy-to-use energy analysis tool. The level of definition required by the designer is high in order to obtain a more precise simulation. The definitions include materials and lighting properties, precise schedules and a good definition for the mechanical system. The calibre of expertise required, therefore, to use the tool is high. Moreover, the tool is adequate for the design's later stages, where the design is almost completed. At this level, it is relatively easy to change the properties of the building, but carrying out changes in the geometry is still rather burdensome (Yezioro et al. 2007).

Genetic algorithms are now finding more widespread application throughout business, scientific and engineering domains. The reasons behind the expanding numbers of applications are clear. These algorithms are computationally simple yet powerful in their search for improvement. Furthermore, they are not fundamentally limited by restrictive assumptions regarding the search space (Goldberg, 1989).

GA has many natural advantages in the modeling and simulation processes of the built environment. They can handle non-linear, ill-defined problems of many dimensions in search spaces with many local minima; moreover, they possess the capacity to process vast quantities of noisy data, efficiently (Coley and Schukat, 2002).

Multi-objective optimization problems require separate techniques that are very different to the standard optimization technique used for single objective optimizations. It is very clear that if there are two objectives to be optimized, it might be possible to locate a best solution in relation to the first objective and another solution that is best with respect to the second.

It is convenient to classify all potential solutions to the multi-objective optimization problems into dominated and non-dominated (Pareto-optimal) solutions. Assuming solution x is dominated, if there exist a feasible solution y not worse than x on all coordinates, i.e, for all objectives $f_i(i=1,\dots,k)$:

$f_i(x) \leq f_i(y)$ for all $1 \leq i \leq k$

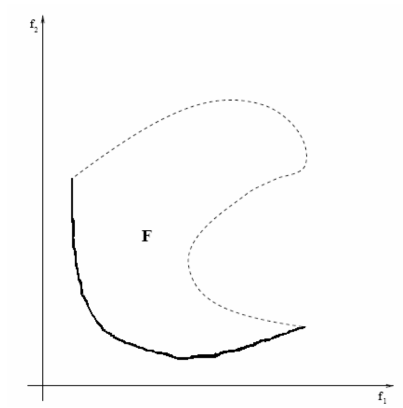

Figure 1 – An example of a problem with two objective functions. The Pareto front is marked with a bold line

If a solution is not dominated by any other feasible solution as illustrated in figure 1, we label it as a non-dominated (or Pareto-optimal) solution. All Pareto-optimal solutions may be of some interest; ideally, the system should report back the set of all Pareto-optimal points. Also, there are some classical methods for multi-objective optimizations. These include a method of objective weighting, where multiple objective functions f_i are combined together into one overall objective function F (Michalewicz, 1996):

$$F(x) = \sum_{i=1}^{k} w_i f_i(x)$$

METHODOLOGY

As mentioned previously, there are three types of shape representation: length-angle, length-bearing and Cartesian representation.

The length-bearing representation (see figure 2) has two major differences in comparison to the other methods. First, bearing, instead of edge angle, is used to determine the direction of each edge. The bearing is the angle between the north direction and an edge, clockwise being positive. Second, the bearing of the first edge replaces the building orientation of the length-angle representation. After these two changes, the direction of each edge becomes an independent variable, thereby reducing gene interactions. The general procedure to establish an n-sided polygon with the length-bearing method requires the following steps:

• Starting from a point P_1, the coordinates of the endpoint P_2 of the first edge can be determined from its length a_1 and bearing α_1.

• The endpoint $P_{i+1}$of the *i*th edge can be determined based on its starting point P_i, its length a_i and bearing α_i. This step is repeated until the point P_{n-1} is defined.

• Given the bearing of the *(n - 1)*th edge, the position of the last point Pn can be calculated to satisfy the fixed area requirement.

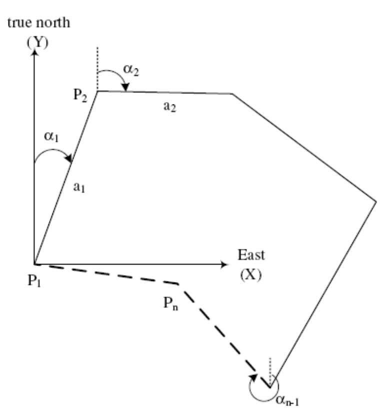

Figure 2 – Length-bearing representation of a polygon

With the length-bearing representation, an n-sided polygon also requires a total of 2 × n - 3 shape-related variables including $a_1,\alpha_1,a_2,\alpha_2,\ldots,a_{n-2},\alpha_{n-2}$, and α_{n-1}.

In this study, we implemented the MOEA toolbox, that functions under Matlab software. We used the DOE22 simulation program by attaching three DLL files [SIMCIO32.dll BDLCIO32.dll D2RESULT.dll] into the main C++ code. Furthermore, we incorporated the main code into a Matlab program by means of the Mex file instruction procedure, which can form a dynamic link to Matlab from the main code. After that, we defined the objective functions and variables within an M- file and began with the MOEA toolbox.

We defined office buildings in eQUEST because the creation of models in it is easier than that of DOE2.2. After forming these models, we used the INP file that was yielded by eQUEST. Then we employed this input file within a generative design procedure by applying MOGAs; each time we needed to evaluate the fitness function, the main code was called and the evaluation accomplished.

ANALYSIS OF THE PROBLEM

The constraint of length-bearing representation is shown in table 1 for all considered shapes in our optimization.

Variable	$a_1,\ldots,a_{n-2}$ (m)		$\alpha_1,\ldots,\alpha_{n-1}$ (rad)		$\theta_1,\ldots,\theta_n$ (deg)	
Minimum and Maximum variable	Min	Max	Min	Max	Min	Max
Quadrilateral	6	61	0	6	30	330
Pentagonal	6	36.5	0	6	30	330
Hexagonal	9	36.5	0	6	30	330

Table 1 – Constraint value for shape optimization problem.

Based on several trial runs, the following GA parameter values was used for all shapes: population size = 30, crossover point = 2, tournament selection with size = 2; for the quadrilateral shapes, the other values were: crossover probability = 0.8, mutation probability = 0.05 and for pentagonal and hexagonal shapes, the other values were 0.7 and 0.04, respectively.

Also, we implemented niching and mating restrictions in our optimization. The niching domain is phenotypic cost and the niching distance is dynamic.

The simulation program is called only for feasible individuals to compute their objective functions.

EXPERIMENT

The weather data, from 1996 to 2000 – that is recorded in three-hour intervals – for Iranian cities are programmed for the study's weather simulation, thus constituting the weather TMY2 file.

The average monthly temperatures during the coldest months [November, December, January, February, and March] in North Tehran were 9.1, 5.9., 2.4, 4.5, and 7.1ºC, respectively. The warmest months [June, July, August, and September] had average monthly temperatures of 25.6, 27.6, 27.6, and 23.4ºC, respectively. The lowest temperature registered in the implemented weather file [TMY] was -7.7ºC, in January, and the highest was 39.6ºC in July. Bushehr's climate was much hotter and sultrier, with temperatures peaking at 45ºC in July and the lowest temperature was 2.4ºC in January. Average monthly temperatures from January to December were 14.9, 16.1, 18.5, 24.8, 29.7, 32.5, 34.2, 34.2, 31.5, 27.6, 21.1, and 17.3 ºC, respectively.

All runs were executed on a computer installed with the Windows XP system (1.63 GHz Dual core processor, 1 GB RAM).

RESULTS

The case study involved the optimization of a single-story office building footprint with quadrilateral, pentagonal and hexagonal shapes across two different weather conditions: the mild and cool North Tehran and the hot and sultry Bushehr. In the simulation program (eQUEST), all values including internal loads and daily operating schedules took the default values for the two story office buildings. Because of the complexity of the existence of a door and window in our optimization process, we assumed that there is no door or window in our model. Only the position, size, and orientation of external walls were optimized.

The number of variables for the quadrilateral, pentagonal, and hexagonal buildings, according to relation 2 × n – 3, were 5, 7, and 9, respectively.

Figures 3 and 4 show the progression of the search for the Pareto front, for north of Tehran's climate, for a quadrilateral office building with 1000m^2 area from generation 60 to generation 230 and Pareto front for Bushehr's climate from generation 20 to generation 200. The Pareto front for the two climates converges on two zones; one with a low perimeter size and the other with a low total annual site energy.

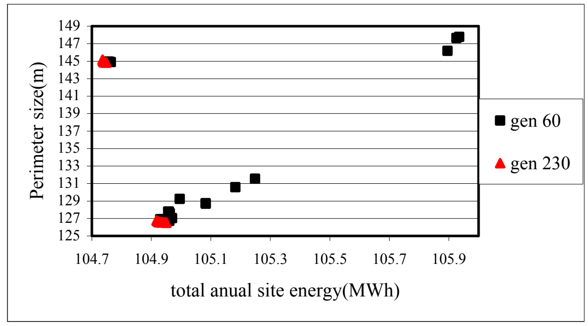

Figure 3 – Pareto front for quadrilateral office building in the north of Tehran climate after 230 generation.

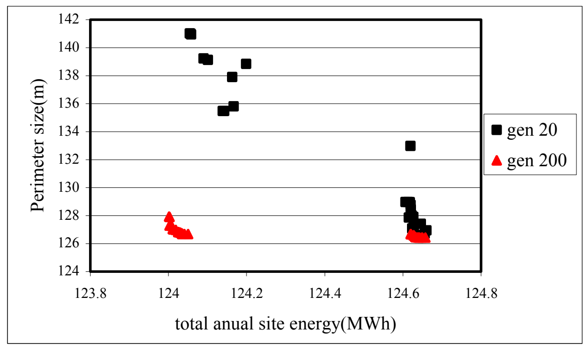

Figure 4 – Pareto front for quadrilateral office building in the Bushehr climate after 200 generation.

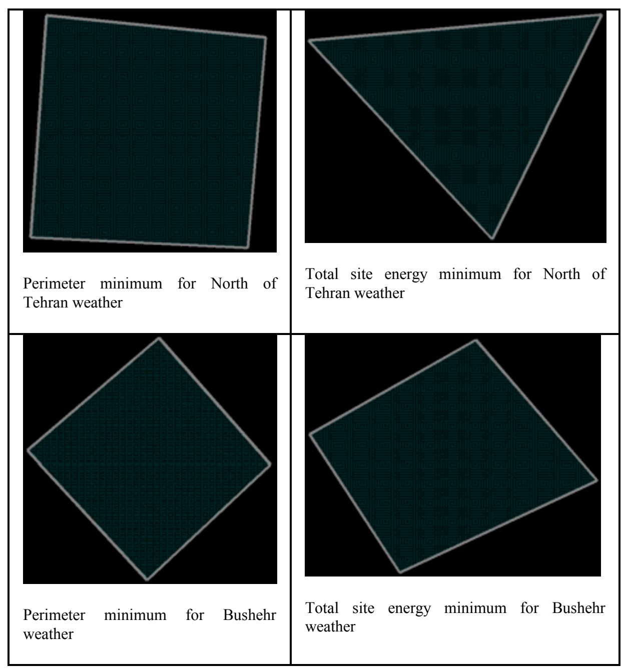

Figure5 – The quadrilateral shape corresponding to Figure 3 and Figure 4 for North Tehran (upper shape) and Bushehr (lower shape) weather

As you can see in figures 3 and 4, the optimal values for the quadrilateral building in terms of perimeter size and annual energy consumption are different in the two climates.

Figure 5 illustrates the shapes corresponding to outcome of minimally low energy and minimal perimeter size, in figures 3 and 4, vis-à-vis North Tehran and Bushehr's weather conditions. This figure indicates that the optimal value for quadrilateral building in North Tehran in terms of energy is that of a triangle whilst in Bushehr, the optimal shape is that of a quadrilateral. Also one observes, in figures 3 and 4, that the optimal value for perimeter size in Bushehr (126.5m) was lower than that in North Tehran (145m). This observation is interesting because we know that the optimal shape for quadrilateral building in terms of perimeter size is the square. However, by applying multi objective genetic algorithm and trading off between the two objectives, the optimal perimeter size for the two weather conditions were different.

One realizes, in figure 6 and figure 7, that the perimeter size for the pentagonal shape is lower in comparison to the quadrilateral shape in both cases (Tehran and Bushehr) but the energy consumption is relatively higher than that in the quadrilateral shape.

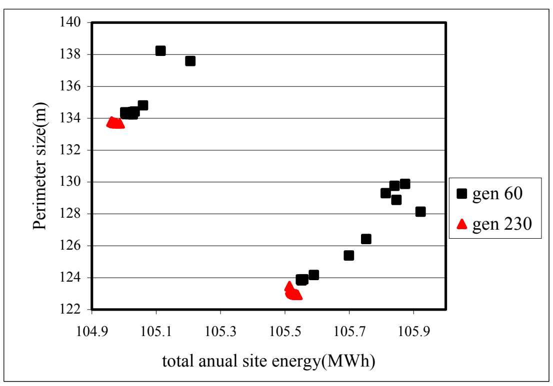

Figure 6 – Pareto front for pentagonal office building in the north of Tehran climate after 230 generation.

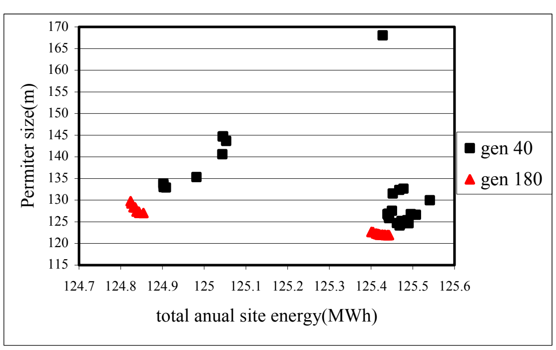

Figure 7 – Pareto front for pentagonal office building in the Bushehr climate after 180 generation.

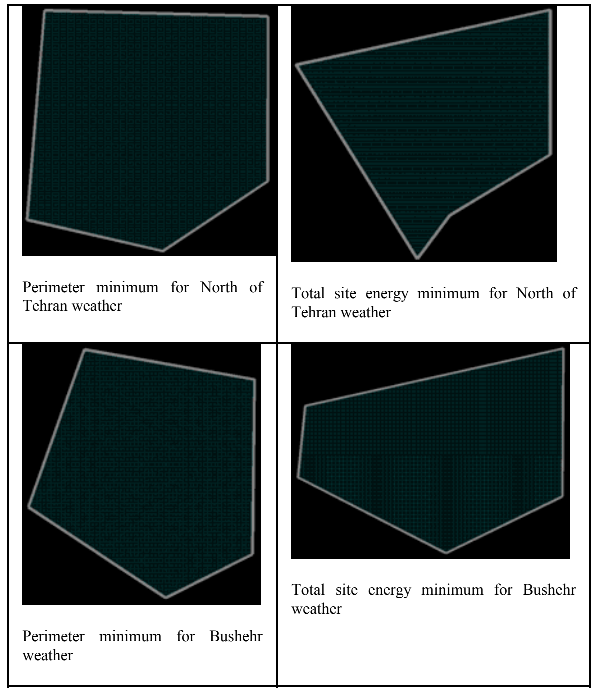

Figure 8 – The Pentagonal shape corresponding to Figure 6 and Figure 7 for North of Tehran (upper shape) and Bushehr(lower shape) weather

Figure 8 illustrates the shapes corresponding to outcome of minimally low energy and minimal perimeter size, in figures 6 and 7, vis-à-vis North Tehran and Bushehr's weather conditions. Regarding North Tehran's weather conditions, in this figure, the shape that accords with minimally low energy is quasi-triangular in configuration (this shape is also realized in figure 5).

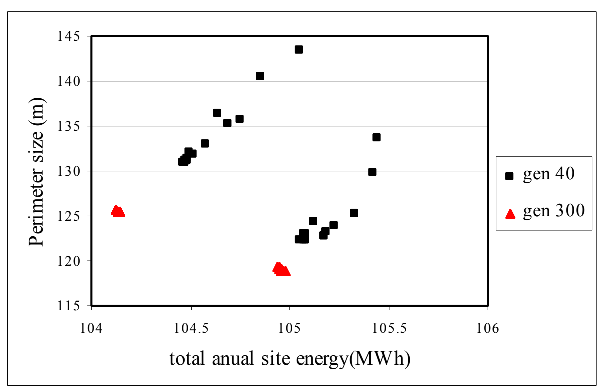

Figure 9 – Pareto front for hexagonal office building in the north of Tehran climate after 230 generation.

Figures 9 and 10 portray an upward trend for both the Pareto front (in N. Tehran's climate conditions, in relation to pentagonal office buildings with 1000m^2 area) from generation 70 to 300 and the Pareto front (in Bushehr's climate) from generation 40 to 300. Also, the Pareto front for the hexagonal shapes (in both climates) converges on two zones: one with a low perimeter size and the other with low total annual site energy.

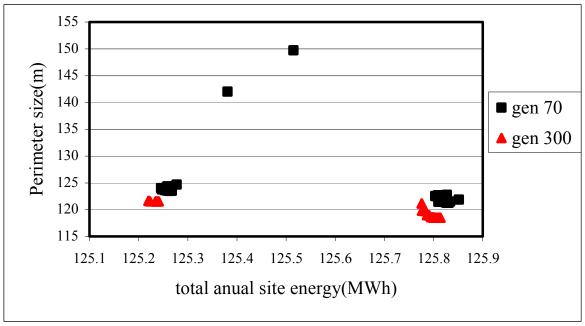

Figure 10 – Pareto front for hexagonal office building in the Bushehr climate after 300 generation.

One observes, in figures 9 and 10, that the perimeter size for the hexagonal shapes is lower in comparison to those for the quadrilateral and pentagonal shapes (both in Tehran and Bushehr) even though the former's energy consumption is relatively higher than those of the corresponding quadrilateral and pentagonal shapes.

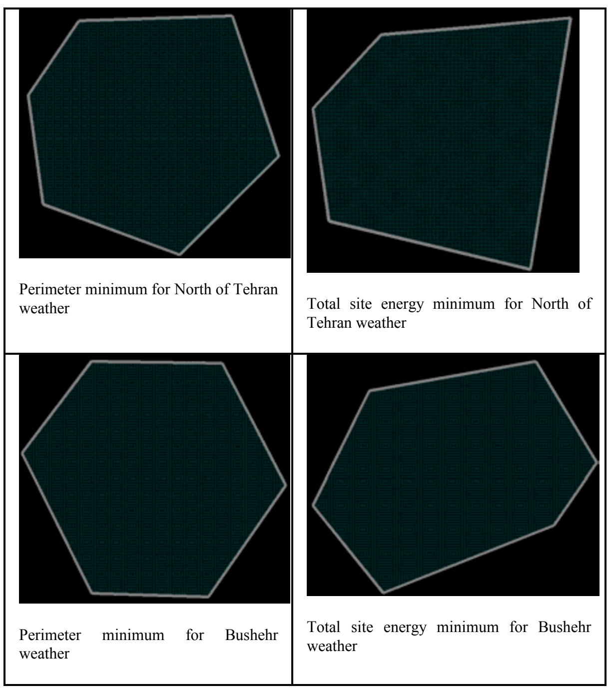

Figure 11 – The Hexagonal shape corresponding to Figure 9 and Figure 10 for North Tehran (upper shape) and Bushehr(lower shape) weather

Figure 11 is corresponding shapes to values in low energy and low perimeter size that obtained from figures 9 and 10 for Hexagonal office building in the North Tehran and Bushehr weather condition.

One observes that the overall orientation of the resulting building shapes for each weather condition, in term of energy consumption and perimeter size in figures 5, 8, and 11 is relatively close to one another.

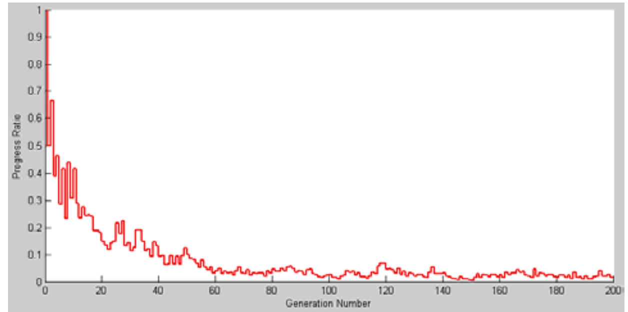

Figure12 – the convergence curve for quadrilateral office building in the Bushehr climate.

For multi-objective, this plot (see figure 12) shows the progress ratio curve over the past specified number of generations. For each generation, the progress ratio will be the average of the current cost and two past generations cost.

CONCLUSIONS

In this study, we investigated the impact of weather conditions upon building shape design with the assistance of two objective genetic algorithms. The results show that there are many differences between the optimal shapes of the buildings.

MOGA has been successfully applied to a number of polygons concerning building energy use and building perimeter size. Since they work with a population of solutions, they naturally provide optimal trade-offs among multiple design criteria. Multiple solutions are of particular value when building footprints are optimization variables, because typically there are many other design criteria to consider, not included in an optimization.

We implemented the concept of green design in our study by the optimization approach and used total annual energy and the perimeter size of the building as two cost functions within the MOEA toolbox.

Optimization can address the disadvantages of the conventional trial-and-error method in exploring different building footprint for green building design. In footprint optimization, the geometrical representation is a fundamental issue to be considered. The representation method used can have a significant impact on the ease of implementation and the performance of optimization. This paper implemented length-bearing method for polygon representation.

There are several avenues for future research. First, with the increasing number of polygon sides, the number of shape-related variables and the chromosome length will increase accordingly. This results in a potential challenge for GA convergence, especially for discrete variables. Last, the next step in this line of research is to progress from two-dimensional building footprint to three-dimensional shape generation and optimization.

In this study we ignored the impact of windows and doors in a simulation program to understand the impact of weather and polygon's side upon the shape of building. It is necessary in real cases for the impact of windows and doors to be taken into account.

ACKNOWLEDGEMENTS

Mojtaba Lajevardi developed this work as part of his MSc dissertation in Mechanical Engineering (Energy Conversion) at Sharif University of Technology, with grant from IFCO (Iranian Fuel Conservation Organization). We would like to sincerely thank professor Larry Degelman, from A&M University of Texas, for assisting us in relation to the weather condition simulations as well as for designing a TMY2 file for some Iranian cities.

REFERENCES

Wang W., Rivard H., and Zmeureanu R. (2006), ‘Floor Shape Optimization for Green Building Design’, *Advance Engineering Informatics*, 20 363-378.

W. Wang, ‘A Simulation-Based Optimization System for Green Building Design’ , *Ph.D. thesis*, Department of Building, Civil, and Environmental Engineering, Concordia University, Montreal, Quebec, Canada, 2005.

Caldas L. G. and Norford L. K. (2003), ‘Genetic Algorithms for Optimization of Building Envelopes and the Design and Control of HVAC Systems’, *Solar Energy Engineering*, Transaction of ASME, 125 343-351.

Coley D. A. and Schukat S. (2002), ‘Low-energy design: combining computer-based optimisation and Human Judgement’, *Building and Environment*, 37 1241-1247.

Wang W., Rivard H., and Zmeureanu R. (2005), ‘Applying Multi-Objective Genetic Algorithms in Green Building Besign Optimization’, *Building and Environment*, 40 1512-1525.

Wang W., Rivard H., and Zmeureanu R. (2005) ‘An Object-Oriented Framework for Simulation-Based Green Building Design Optimization with Genetic Algorithms’, *Advance Engineering Informatics*, 19 5-23.

Yezioro A., Dong B., and Leite F. (2007) ‘An Applied Artificial Intelligence Approach Towards Assessing Building Performance Simulation Tools’, *Energy and Building*, ARTICLE IN PRESS.

Goldberg D.E. (1989) ‘*Genetic Algorithms in Search, Optimization and Machine Learning*’, Addison-Wesley.

Michalewicz Z. (1996), *Genetic Algorithms + Data Structures = Evolution Programs*, Springer-Verlag.