COST–EFFECTIVE, ENERGY–EFFICIENT SOLUTIONS FOR BUILDING ENVELOPE: A MULTI–OBJECTIVE OPTIMIZATION CASE STUDY

Abstract

The renovation of a building entails not just the fulfillment of functional demands, but also considerations such as investment costs, energy consumption, and occupant well-being. Building energy retrofitting should pursue "cost-optimal levels." To do so, the present study proposes a method aimed at "defining the energy performance of buildings' shells" with 'optimal cost levels.' With this aim, the multi-objective optimization method is adopted. Using the genetic algorithm, the optimization method a connection is defined between the optimization algorithm in the jEplus software (as the optimization engine) and the EnergyPlus™ software (as the simulation engine), and allows the designer to evaluate a range of different options and select the best. In this paper, a developed method for energy optimization of reference buildings is conducted. Simulation-based simulation results indicate that the energy saving rate in the four different climates of Iran is 29% to 58% lower than the base model. One of the results available can be best suited for expert judgment or decision making.

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Keywords

Building environment, energy efficiency, investment cost, multi-objective optimization, genetic algorithm

Introduction

Research has consistently shown the emerging role of existing buildings in the context of energy consumption (Itard & Meijer, 2008). Therefore, the potential of energy saving in the building sector is remarkable (Tuominen et al., 2012); so it is fundamental to retrofit existing buildings in a procedure in which they consume minimum energy with reasonable renovation investment costs. Productivity enhancement of existing buildings is becoming a practical step for reducing environmental impacts and increasing cost control (Bolattürk, 2008).

Hence, energy efficiency in building stock has become a potential approach to accede sustainability in the built environment and a lucrative source for builders and investors (Aslani et al., 2019). Knowing that, for many years to come, measures taken in existing buildings will have a significant effect on the total energy demand in the building stock. The rapid enhancement of energy efficiency in existing buildings is essential for energy consumption reduction and the cultivation of environmental sustainability. Existing building retrofits offer many challenges and opportunities. By applying the cost concept to exergy, García Kerdan et al. (2017) used exergoeconomic analysis to find the optimal insulation thickness in four different climates in Turkey.

Due to its definitive impact on energy consumption, building envelope plays a crucial role in the investment costs (ASHRAE, 2014), and the pattern of energy demands will change after the retrofit of the building enclosure (Straube & Burnett, 2005). Building envelope energy performance involves numerous parameters including wall and roof insulation, window area, window glazing, window shading, climate zones, and building orientation (Yang et al., 2017). Each of the features affects the energy efficiency of the building enclosure (Méndez Echenagucia et al., 2015).

Therefore, determining the proper components of the building envelope is controversial, in that economic considerations should also be noticed (Asadi et al., 2014; Evins, 2015; Karmellos et al., 2015; Mostavi et al., 2017). Because a building with the least amount of energy consumption is unlikely to be cheap, the energy analysis of the building envelope becomes more complicated. Besides, most of the cost-saving patterns are associated with lower energy consumption. Traditionally, this type of analysis has been carried out using DOE-2 (DOE-2.3V 49, 2016) or EnergyPlus (EnergyPlus V 8.8.0, 2018). In such approaches, the interaction of design variables with other variables as well as the optimized envelope effect on the energy consumption of the building is ignored (Tian, 2013); in addition, under the best optimization based on simulation, this approach is practically “one factor at a time” (Delgarm et al., 2018).

In addition, a single-objective approach is very time consuming and impractical for multidisciplinary approaches as nonlinear interactive effects of different variables should be evaluated (Kheiri, 2018). As a result, technical specifications of the building envelope implemented by typical parametric design methods are not fully reliable. For this reason, “simulation-based optimization” has been developed along with the progress of computer science in the last two decades to increase the productivity of a building (Nguyen et al., 2014). Ascione et al. (2015), using the genetic algorithm, achieved optimal values of building envelope components based on their energy consumption and investment cost. Delgarm et al. (2016) also found an optimal amount of building envelope variables using the genetic algorithm considering the cooling and heating demands. Zhang et al. (2017) investigated three objective functions, energy, lighting, and thermal comfort, for achieving optimal values of the building envelope. In a recent study, Gou et al. (2018) optimized neural network and genetic algorithms to optimize the building envelope to achieve the highest thermal comfort and minimum energy requirements. Reynolds et al. (2018) applied a similar optimization with emphasis on the design of the mechanical system. Sharif and Hammad (2019), focusing on the retrofit of existing building envelopes, optimized their Life Cycle Cost (LCC) and environmental impact using Life Cycle Assessment (LCC).

Currently, there are several optimization algorithms available (Ascione et al., 2019), among which researchers often prefer to use random-based population-based algorithms. The present study provides a comprehensive study on the effect of building envelope parameters, including window size, glass type, and insulation thickness, on energy consumption and construction costs. This study investigates the feasibility of applying a multi-objective optimal model on building envelope design which involves an energy performance of building envelope integration model with a multi-objective optimizer.

Research Methodology

The approach of this research, based on multi-objective optimization, is proposed to evaluate the cost-optimal solution concerning energy efficiency. EnergyPlus has been selected as a tool for building information simulation. Particularly, the jEPlus optimization engine has been selected to optimize multi-objective problems using a genetic algorithm and carry out the energy-simulation (Zhang, 2009).

The correlation between variables and objectives was tested using Sobol method in SimLab. Python scripts were used in both pre-processing of the models and post-processing of the simulation results.

Application to a Case Study

In the present study, to investigate the sensitivity analysis and optimization process, the method used for educational class to study the effect of parameters on energy performance in four main climates of Iran have been implemented.

In Figure 1, a view of the classroom in Tehran has been illustrated. All the space around the room is ventilated and temperature-sensitive and all internal walls are adiabatic.

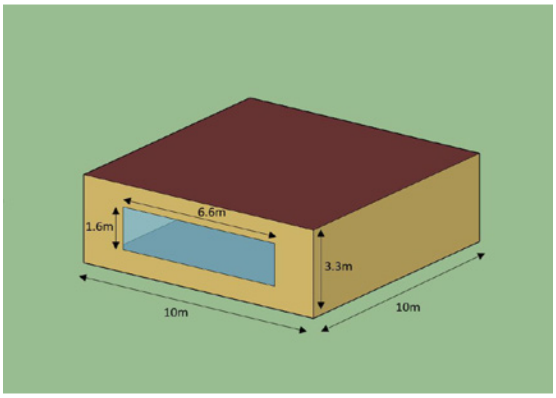

Figure 1: A view of model in Sketchup.

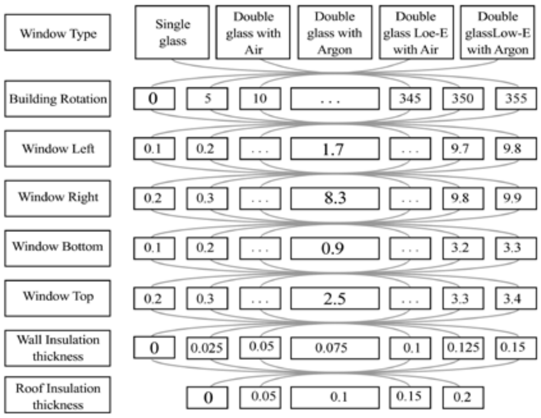

Figure 2: Tree diagram of design variables.

Glass type	U	SHGC	TSOL	TVIST
Single glass 6mm	5.849	0.861	0.837	0.898
Double glass 6mm/13mm Air	2.72	0.764	0.705	0.812
Double glass 6mm/13mm Argon	2.556	0.764	0.705	0.812
Double glass-Low-E 6mm/13mm Air	1.761	0.691	0.624	0.744
Double glass-Low-E 6mm/13mm Argon	1.41	0.691	0.624	0.744

Table 1: Window types used in the study.

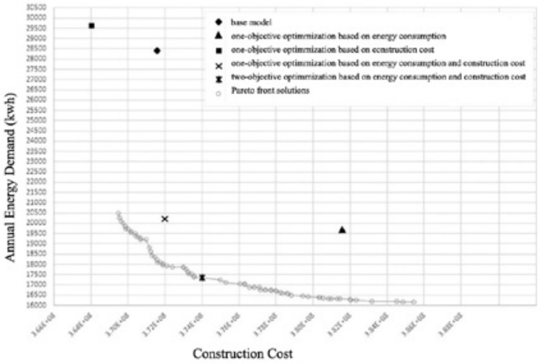

Figure 3: Comparison of single-objective and two-objective optimization.

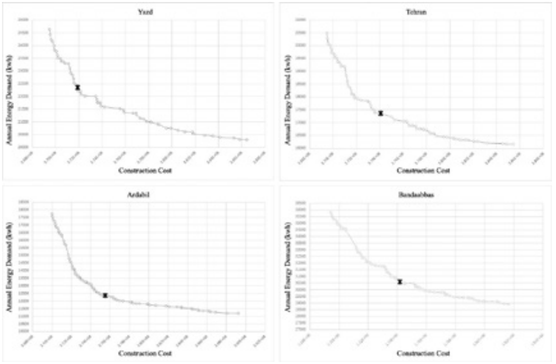

Figure 4: Optimum points in four climates.

The class is considered to be 10 meters in length and width and 3.5 meters in height. The wall facing the south of the simulated room has a double-glass window with a width of 6/6 * 1/6 m with a window-to-wall ratio of 30%. In the classroom, an ideal air-conditioning system is considered. Schedules for occupant presence, illumination, air infiltration, and setpoint were provided in EnergyPlus, which maintains the temperature of the classroom at 21 degrees Celsius in winter conditions and 28 degrees Celsius in summer conditions. Also, the daylight-lighting control sensor is fitted with a brightness up to 600 and at least 300 lux at the height of 80 cm from the floor, in the center. In addition, according to timetables. U-values of the materials are 2.8, 4.2, and 5.5 in the walls, floors, and windows, respectively.

The tree diagram in Figure 2 shows the design variables, and Table 1 shows the window types used in the analysis of the research.

As window's dimensions increase, we see an increase in the entrance of light, which reduces the need for artificial light. In cold seasons, this will cause more sunlight to enter, which is desirable. While in the warm seasons, this increase in the window level increases the entry of heat into the interior and increases cooling. In addition to all, the larger the window area, the more construction cost.

In the following, to analyze the sensitivity of each parameter, we carried out sensitivity analysis in SimLab. By analyzing the general indexes of sensitivity of each parameter considering two objectives of total energy consumption and construction costs, we came to conclude that the window size has the greatest effect. In addition to the dimensions of the window, its position on the wall is also of particular importance. For this reason, in this study, the limits of the window position relative to the coordinates of the wall are defined. After window dimensions, the most effective variables are the roof insulation and rotation of the building, respectively. Finally, the type of glass has the least importance compared to other parameters.

Results and Discussion

The results showed that single-objective optimization based on total energy with a 21% increase in the construction cost can reduce the energy cost by 31%. While based on construction costs with a 2% reduction in costs, it has a 4% increase in energy consumption. Considering both construction cost and the total energy, it had a rise of 0.5% in cost and 28% of energy consumption reduced.

In two-objective optimization, a set of optimized points is presented as a Pareto front. Figure 3 presents the results of two-objective optimization with the results of a single-objective. According to this figure, the amount of cost needed for single-objective optimization would result in the consumption of 20190 kWh of annual energy, the corresponding image which is Pareto graph with an annual energy consumption of 17950 kWh. Figure 4 shows a more appropriate scale of the Pareto front for Tehran. This trend is also carried out for other cities, such as Yazd, Ardabil, and Bandar Abbas, where Figure 4 illustrates the possible solutions in these cities.

The final profile of the building envelope for the four climates of Iran is shown in Table 2. As a result, two-objective optimization can decrease by 37% in energy consumption, which reduces costs by 17%.

Results of multi-objective optimization in four climates show that the total cost of energy and construction can be reduced from 28% in single-objective optimization to 39.5% in two-objective optimization. However, in single-objective optimization, the dimensions of the window are 10% which cannot transmit the desired lighting throughout the day, while two-objective optimization with an emphasis on daylight brightness has increased by 15%. Results show with an increase of less than 1% of the cost of construction in all cities, we will have a significant reduction in annual energy consumption. Also, the size of the opening in the cold climate is more than other cities.

Conclusion

In this paper, a multi-criteria optimization method was implemented to minimize energy consumption and construction cost. The results of parametric studies, sensitivity analysis of variables, and single-parameter optimization and multiple criteria were analyzed. Decision-making variables for optimization, including building orientation, window size, type of glass, the thickness of roof and wall insulation, were evaluated. By performing sensitivity analysis, the least significant parameters were eliminated. Results of sensitivity analysis showed that the parameters of the window dimensions, the thickness of the insulation of the ceiling and the wall were respectively influential variables according to objectives. The results of the Pareto front in two-objective optimization showed that the conditions are far more satisfying than the single-objective one.

The results of this research indicate the vivid effect of interactive behavior of parameters with each other relative to the objective functions; in this type of optimization, designers also have greater freedom of action than the obtained solutions and can be more effective about the decision-making process optional choice.

Decision City Variables	**Tehran**	**Yazd**	**Ardebil**	**Bandarabbas**
Building orientation (°)	15	25	10	20
Window width (m)	2.7	2.9	3.5	3.2
Window height (m)	1.9	1.7	1.9	1.9
OKB (m)	1.2	1.2	1.2	1.2
WWR %	15	14	19	17.3
Window type	Double glass with Argon	Double glass with Argon	Double glass with Argon	Double glass with air
Wall insulation thickness (m)	0.025	0	0.05	0
Roof insulation thickness (m)	0.075	0.05	0.075	0.075
Annual energy consumption (kwh)	17351.52	22327.76	12376.01	30569.83
Construction cost (rial)	3.74E+08	3.72E+08	3.75E+08	3.74E+08

Table 2: Optimum Design Parameters Based on Multi-Object Optimization in different climates in Iran.

References

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2014). *ASHRAE Design Guide, Advanced Energy Design Guide for Small to Medium Office Buildings*, Atlanta, GA.

Asadi, E., Silva, M. G. d., Antunes, C. H., Dias, L., & Glicksman, L. (2014). Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application. *Energy and Buildings, 81,* 444–456. https://doi.org/10.1016/j.enbuild.2014.06.009

Ascione, F., Bianco, N., De Stasio, C., Mauro, G. M., & Vanoli, G. P. (2015). A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. *Energy and Buildings, 88,* 78–90. https://doi.org/10.1016/j.enbuild.2014.11.058

Ascione, F., Bianco, N., Mauro, G. M., & Vanoli, G. P. (2019). A new comprehensive framework for the multi-objective optimization of building energy design: Harlequin. *Applied Energy, 241,* 331–361. https://doi.org/10.1016/j.apenergy.2019.03.028

Aslani, A., Bakhtiar, A., & Akbarzadeh, M. H. (2019). Energy-efficiency technologies in the building envelope: Life cycle and adaptation assessment. *Journal of Building Engineering, 21,* 55–63. https://doi.org/10.1016/j.jobe.2018.09.014

Bolattürk, A. (2008). Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey. *Building and Environment, 43*(6), 1055–1064. https://doi.org/10.1016/j.buildenv.2007.02.014

Delgarm, N., Sajadi, B., Azarbad, K., & Delgarm, S. (2018). Sensitivity analysis of building energy performance: A simulation-based approach using OFAT and variance-based sensitivity analysis methods. *Journal of Building Engineering, 15,* 181–193. https://doi.org/10.1016/j.jobe.2017.11.020

Delgarm, N., Sajadi, B., Delgarm, S., & Kowsary, F. (2016). A novel approach for the simulation-based optimization of the buildings energy consumption using NSGA-II: Case study in Iran. *Energy and Buildings, 127,* 552–560. https://doi.org/10.1016/j.enbuild.2016.05.052

DOE-2.3V 49. (2016). Lawrence Berkeley National Laboratory (LBNL).

EnergyPlus V 8.8.0. (2018). U.S. Department of Energy (DOE).

Evins, R. (2015). Multi-level optimization of building design, energy system sizing and operation. *Energy, 90,* 1775–1789. https://doi.org/10.1016/j.energy.2015.07.007

García Kerdan, I., Raslan, R., Ruyssevelt, P., & Morillón Gálvez, D. (2017). ExRET-Opt: An automated exergy/exergoeconomic simulation framework for building energy retrofit analysis and design optimisation. *Applied Energy, 192,* 33–58. https://doi.org/10.1016/j.apenergy.2017.02.006

Gou, S., Nik, V. M., Scartezzini, J.-L., Zhao, Q., & Li, Z. (2018). Passive design optimization of newly-built residential buildings in Shanghai for improving indoor thermal comfort while reducing building energy demand. *Energy and Buildings, 169,* 484–506. https://doi.org/10.1016/j.enbuild.2017.09.095

Itard, L., & Meijer, F. (2008). *Towards a Sustainable Northern European Housing Stock.* Delft University Press.

Karmellos, M., Kiprakis, A., & Mavrotas, G. (2015). A multi-objective approach for optimal prioritization of energy efficiency measures in buildings: Model, software and case studies. *Applied Energy, 139,* 131–150. https://doi.org/10.1016/j.apenergy.2014.11.023

Kheiri, F. (2018). A review on optimization methods applied in energy-efficient building geometry and envelope design. *Renewable and Sustainable Energy Reviews, 92,* 897–920. https://doi.org/10.1016/j.rser.2018.04.080

Méndez Echenagucia, T., Capozzoli, A., Cascone, Y., & Sassone, M. (2015). The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. *Applied Energy, 154,* 577–591. https://doi.org/10.1016/j.apenergy.2015.04.090

Mostavi, E., Asadi, S., & Boussaa, D. (2017). Development of a new methodology to optimize building life cycle cost, environmental impacts, and occupant satisfaction. *Energy, 121,* 606–615. https://doi.org/10.1016/j.energy.2017.01.049

Nguyen, A.-T., Reiter, S., & Rigo, P. (2014). A review on simulation-based optimization methods applied to building performance analysis. *Applied Energy, 113,* 1043–1058. https://doi.org/10.1016/j.apenergy.2013.08.061

Reynolds, J., Rezgui, Y., Kwan, A., & Piriou, S. (2018). A zone-level, building energy optimisation combining an artificial neural network, a genetic algorithm, and model predictive control. *Energy, 151,* 729–739. https://doi.org/10.1016/j.energy.2018.03.113

Sharif, S. A., & Hammad, A. (2019). Simulation-Based Multi-Objective Optimization of Institutional Building Renovation Considering Energy Consumption, Life-Cycle Cost and Life-Cycle Assessment. *Journal of Building Engineering, 21,* 429–445. https://doi.org/10.1016/j.jobe.2018.11.006

Straube, J. F., & Burnett, E. F. P. (2005). *Building science for building enclosures.* Building Science Press.

Tian, W. (2013). A review of sensitivity analysis methods in building energy analysis. *Renewable and Sustainable Energy Reviews, 20,* 411–419. https://doi.org/10.1016/j.rser.2012.12.014

Tuominen, P., Klobut, K., Tolman, A., Adjei, A., & de Best-Waldhober, M. (2012). Energy savings potential in buildings and overcoming market barriers in member states of the European Union. *Energy and Buildings, 51,* 48–55. https://doi.org/10.1016/j.enbuild.2012.04.015

Yang, M.-D., Lin, M.-D., Lin, Y.-H., & Tsai, K.-T. (2017). Multiobjective optimization design of green building envelope material using a non-dominated sorting genetic algorithm. *Applied Thermal Engineering, 111,* 1255–1264. https://doi.org/10.1016/j.applthermaleng.2016.01.015

Zhang, A., Bokel, R., van den Dobbelsteen, A., Sun, Y., Huang, Q., & Zhang, Q. (2017). Optimization of thermal and daylight performance of school buildings based on a multi-objective genetic algorithm in the cold climate of China. *Energy and Buildings, 139,* 371–384. https://doi.org/10.1016/j.enbuild.2017.01.048

Zhang, Y. (2009). *Parallel energyplus and the development of a parametric analysis tool* [Paper presentation]. Proceedings of the 11th International IBPSA Conference, Scotland.