OPTIMUM GREEN BUILDING DESIGN USING HYBRID METAHEURISTICS

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УДК: 728:502
DOI:10.14415/konferencijaGFS 2015.005

Summary: *Although energy efficient buildings are more common than they used to be, they are still considered too expensive, primarily because of relatively high prices of good insulation materials and equipment. Therefore, green building design has to meet two often confronted demands – minimal construction cost while maintaining minimal environmental impact. This paper presents optimum design method based on hybridization of different metaheuristics.*

Keywords: *Green building, optimization, hybridization, metaheuristics.*

1. INTRODUCTION

Reduction of the energy consumption without compromising living standard has become very important issue in civil engineering and building industry. This problem includes numerous independent and often contradictory aspects because design of the energy-efficient building usually includes more expensive insulation materials and better heating, ventilating and air-conditioning systems, which all can have significant impact on the total price of the construction. That indicates that a compromise between construction cost and energy efficiency should be find. This problem can not easily be solved without an efficient multi-objective decision making tool which would successfully include all of them in order to find optimal solution that would meet all given demands.

Meta-heuristics have been proven to be very successful tool for solving this kind of optimization problems, allowing a designer to make a choice among several solutions that are optimal considering different objectives and thus not comparable between each other (Pareto optimum). Additional problem in this class of problems is the fact that there is no universally best meta-heuristic that would guarantee that obtained solution is

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the best one. Furthermore, meta-heuristics which are good for global search, such as Genetic Algorithms or Big Bang – Big Crunch algorithm, sometimes can have difficulty with premature convergence to the local optimum due to the different nature of the variables and demands, as in case of optimum green building design [1]. On the other hand, meta-heuristics that are very efficient in detailed search of relatively small search space, can be too slow and inefficient for more complex problems [2]. This can be solved by their hybridization [3–5] in order to use the best features of each method. This paper presents hybridization of Big Bang – Big Crunch algorithm (BB-BC) and tabu search (TS).

Further inconvenience in solving this problem is the fact that in discussing energy efficiency and using renewable energy sources, a building can not be observed independently of its natural environment. This demands inclusion of additional software, such as EnergyPlus which would provide energy consumption data for different types and kinds of buildings and different lighting and HVAC systems according to the local meteorological data of a given region. Pitman and King [6] proposed methodology for the building shape optimization in order to establish balance between received solar energy via façade and energy consumption by lighting and HVAC systems using the EnergyPlus software. Other authors have also researched methods for maximizing energy efficiency and minimizing the cost and at the same time by optimizing type and of quality of windows and insulation materials [7], room shape and orientation, as well as the windows size and positioning [8] or architectural and constructional aspects of the building and performances of the HVAC systems [9,10]. In order to include different environment features into calculus, EnergyPlus software is additionally implemented in two meta-heuristics hybrid.

2. PROBLEM FORMULATION

As it was said in the introduction, optimal design of an energy efficient building has to meet two confronted demands: to minimize total cost of construction, and to minimize environmental impact and energy consumption, which is usually obtained by the implementation of expensive insulation materials and equipment. Consequently, there is no unique, i.e. the best solution, but a number of more or less acceptable ones among which designer chooses a satisfying one considering given demands and limitations. Therefore, optimization task cannot be formulated by a single objective function, but requires at least two functions and belongs to the area of multi-objective optimization.

Because of the complexity of the problem, the two objective functions to be minimized in this research were the life-cycle cost (C) and the life-cycle environmental impact (EI):

$$\mathrm{Min:C} = IC + OC \quad (1)$$

$$\mathrm{Min:EI} = EC + EO \quad (2)$$

where *IC* is the initial construction cost (€); *OC* is the present worth of life-cycle operating costs (€); *EC* is the environmental impact (MJ) due to building construction, and *EO* is the environmental impact (MJ) due to the building operation for heating, cooling, lighting and other similar processes. The environmental impact of a building is evaluated by the cumulative exergy consumption [11], where exergy is defined as "the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the common components of nature" [12]. EC is represented by the embodied energy of all fuels consumed in pre-operation phase, while EO is expected total energy consumption during the life of a given building.

3. OPTIMIZATION TOOLS

In 2006, Erol and Erskin introduced a new optimization method inspired by one of the theories of the evolution of the universe, namely the Big Bang and Big Crunch theory [13]. During the past few years, this method has been proven to has a low computational time and high convergence speed. The Big Bang–Big Crunch (BB–BC) optimization method similarly generates random points in the Big Bang phase and shrinks these points to a single representative point via a center of mass in the Big Crunch phase. After a number of sequential Big Bangs and Big Crunches where the distribution of randomness within the search space during the Big Bang becomes smaller and smaller about the average point computed during the Big Crunch, the algorithm converges to a solution. The BB–BC method has been shown to outperform the enhanced classical Genetic Algorithm for many benchmark test functions [14].

Although BB-BC algorithm has been proven able to locate promising regions for global optima in a search space, it sometimes can have a problem with finding the exact minimum or maximum, especially if the search space is very large or there is too much variables. This can be solved by improving the solution obtained in each iteration using some other optimization method.

In the field of optimization problems, tabu search (TS) is often used as a 'higher' heuristic procedure for enabling the other methods to avoid the trap of local optimum [1-5]. TS operates on a single solution at a time and uses problem-specific operators to explore a search space and memory (called the tabu list) while keeping track of parts already visited. By guiding the optimization to the new areas, TS is able to overcome local minima and to reach the global optimum [15].

In this case, after using the Big Crunch phase in every step of the evolution, the solution with best result is selected as tabu and added to tabu list. Solutions in tabu list have an aspiration time which decreases in each iteration. When the aspiration time of a given solution in tabu list fall down to zero, that solution will be deleted from this list and added to aspiration list. After finding tabu solution, solutions in current iteration that are similar to it will be are replaced with the solution in aspiration list. If the aspiration list is empty, these solutions will be replaced with the ones from the last iteration which have the best (minimal or maximal) fitness value.

EnergyPlus is energy analysis software which enables the evaluation of the energy consumption for different types of buildings and HVAC systems according to the meteorological data of a given region and the building orientation. Thanks to its structure and the fact that input and output are done via textual files, it is very convenient for merging and hybridization with other programs and for implementing independently developed plug-ins, subroutines and tools. In presented research, it was used to calculate energy consumption for automatically generated solutions (combination of parameters) obtained by the hybrid BB-BC-TS algorithm.

4. CASE STUDY

The building present in this case study is hexagonal two-story building located in Belgrade, Serbia, with floor area of 500 m^2 and floor-to-floor height of 3.0 m. The heating season is from October 15th to March 15th, while the cooling season is from June 15th to August 31st. The indoor design temperatures are set to 22°C for both the heating and cooling, without night setback or setup. A period of 25 years is used in the life-cycle analysis for building performance.

The variables considered in presented study are categorized into four groups: shape, structure, envelope configuration and overhang. Building shape is defined by the edge lengths (5–50 m) and the angles between edges (15°–180°). The structure-related variable defines one of two different available alternatives for the building structural system – steel frame and concrete frame. Both of them have the same two possible exterior wall types: concrete block wall and steel-stud wall. However, they have different floor types: the steel deck on open web steel joist floor type is used for the steel frame while a cast-in-place concrete floor type is used for the concrete frame. The concrete block wall consists of cladding, rigid insulation, vapour barrier, concrete block, and finish, while the steel-stud wall consists of cladding, rigid insulation, air barrier, sheathing, steel-stud with cavity insulation, vapour barrier, and finish. Only the insulation layers are optimized because all other layers have minor impact on the two considered performance criteria. The overhang depth varies between 0.1 and 1.2 m, while the overhang height is fixed to be 0.2 m.

The building envelope system can be divided into opaque walls, floors, roofs, and windows. Six window types are available for each façade, as follows: double clear glazing; reflective double glazing; low-e double glazing with a coating with emissivity 0.2 or 0.1 on the exterior of the inside pane and low-e double glazing with a coating with emissivity 0.2 or 0.1 on the interior of the outside pane.In order to consider alternative wall constructions simultaneously, both wall type and wall layer are represented as related discrete variables. The same principle applies to roof type and roof layers, floor type and floor layers. In addition, this study considers window type and window ratio for each façade as variables. The overhang design is closely related to the window below it. In this study, the overhang width is the same as the window width, which is set equal to the length of the corresponding wall. The overhang-related variables are: overhang type (a discrete variable that indicates the possible overhang types for each façade, including the option of no overhang); overhang depth for each façade and overhang height for each façade.

Obtained results are visibly grouped into two isolated regions – one with lower costs and larger environmental impacts (the best solution: $6.75 \cdot 10^5$€ and $2.850 \cdot 10^7$ MJ), and the other one, with lower environmental impacts but larger costs (the best solution: $4.23 \cdot 10^5$€ and $2.144 \cdot 10^7$ MJ). These two Pareto zones are directly connected with the allowed structural systems. The steel frame system has a lower cost but higher environmental impacts than the concrete frame system. The steel-stud wall is the optimal wall type for all solutions. As it was expected and logically assumed, the longest wall in all solutions (length ranging from 24 to 30 m) is south-oriented in order to take advantage of the passive solar heating. Since the building in this case study has a fixed floor area and height, the perimeter can be employed as a valuable indicator to measure the compactness of a building. The general trend is that the perimeter increases with the life-cycle cost and that the LCC increases and the LCEI decreases as the perimeter of the pentagon and the length of its south edge increase. All solutions have the optimal window type as the double glazing with coating. Differences between two proposed types of glazing were negligible. The window ratio on the south façade varies while it has converged to the lower bound 0.2 for all other façades. If overhang is used, its depth takes the lower bound 0.1 m for most solutions. The largest overhang depth is 0.25 m for the solutions with the longest south wall and the largest window ratio. There should be no overhang on non-south façades because there is no direct sun on the north façade and the solar angle is low for the east and west façades.

Obtained solution is remarkably better than the one achieved with BB-BC olny, which proves that hybrid consisting of adequately chosen meta-heuristics outperforms results of one search method only.

5. CONCLUSION

Since total price of a building and its environmental impact are usually directly confronted aspects, the decision-maker should be aware of all their advantages and disadvantages. Therefore, numerical analysis for exploring different possibilities should not be exclusive, i.e. not to provide only one solution, but to offer at least several solutions in order to enable decision-maker to get a good insight and to make the most appropriate choice considering given situation. Results of the presented research show that hybrid of different meta-heuristics outperforms solutions obtained by only one search method and that it can be successfully used for optimum design of green buildings.

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ОПТИМАЛНО ПРОЈЕКТОВАЊЕ ЗЕЛЕНИХ ЗГРАДА ПРИМЕНОМ ХИБРИДНИХ МЕТАХЕУРИСТИКА

Резиме: *Иако су данас енергетски ефикасне зграде много уобичајеније него раније, још se сматрају прескупима, првенствено због релативно високих цена квалитетних изолационих материјала и опреме. Због тга при пројектовању зелених зграда треба задовољити два неретко супротстављена захтева – истовремену минимизацију цене конструкције уз минималан утицај на околину. У раду је приказана метода оптималног пројектовања зелене куће применом хибридних метахеуристика.*

Кључне речи: *Зелене зграде, оптимизација, хибридизација, метахеуристике.*