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OPTIMAL ENERGY EFFICIENT BUILDING DESIGN USING IMPROVED EVOLUTIONARY ALGORITHM

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ABSTRACT

Considering energy efficiency and sustainable development on one side and economy aspects on the other, optimal building design has to meet two confronted demands: to minimize total cost of the construction and to minimize energy consumption, which is usually obtained by implementation of expensive insulation and equipment. This paper presents solving methodology using evolutionary algorithm improved by introducing the tabu search module and combined with EnergyPlus software. The results are demonstrated on the example of optimization of insulation materials and orientation angle of a given building, confirming that proposed methodology successfully meets design demands.

Key words: *Energy efficiency, evolutionary algorithm, tabu search, Energy Plus, multi-objective optimization*

OPTIMALNO PROJEKTOVANJE ENERGETSKI EFIKASNIH ZGRADA PRIMJENOM POBOLJŠANOG EVOLUCIONARNOG ALGORITMA

REZIME

Uzimajući u obzir energetsku efikasnost i održivi razvoj s jedne strane i ekononmski aspekt s druge, optimalno projektovanje treba da zadovolji dva suprotstavljena zahteva: da minimizuje cenu konstrukcije i da minimizuje potrošnju energije, što se uglavnom postiže primenom skupih izolacionih materijala i opreme. U ovom radu prikazana je metodologija za rešavanje datog problema primenom evolucionog algoritma poboljšanog modulom za tabu pretragu i kombinovanjem sa softverom EnergyPlus. Rezultati za primer optimizacije izolacionih materijala i ugla položaja date zgrade potvrđuju da prikazana metodologija ispunjava navedene projektne zahteve.

Ključne reči: *Energetska efikasnost, evolucioni algoritam, tabu pretraga, EnergyPlus, višekriterijumska optimizacija*

INTRODUCTION

Although energy consumption is one of the greatest global concerns at the moment, the greatest part of the energy still comes from non-renewable sources. Therefore, reduction of the energy consumption without compromising living standard has become very important issue in civil engineering and building industry. On the other hand, 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 (HVAC) 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.

Besides that, HVAC systems are usually the most electricity demanding equipment in a building, especially in public buildings and industrial facilities. While reduction of these utilities can significantly reduce total energy consumption, it can also have negative impact on the people who live or work in that building. Another example of conflicted interests is the windows size. While larger windows allow better use of daylight and reduction of electricity consumption for lighting, they would also produce greater heat loss than the walls and consequently increase the energy consumption for heating.

These examples, with other conflicted aims in this field, indicate that 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 which would meet all 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). Evolutionary algorithms (EA) and tabu search (TS) have been proven to be satisfying tools for solving similar problems [1,2] although, due to the different nature of the variables and demands, sometimes can have difficulty with premature convergence to the local optimum, which can be solved by their hybridization [3,4,5] in order to use the best features of each method.

Further inconvenience in solving this problem is the fact that, if we talk about 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].

The aim of research presented in this paper was to improve EA features by hybridizing it with TS and to combine it with simulation software EnergyPlus in order to find optimal position of a given building and insulation materials.

OPTIMIZATION TOOLS

Evolutionary algorithms

Evolutionary algorithms (EA) are a special class of global optimization methods, basedon the theory of evolution, able to minimize (or maximize) objective function $G(x)$, where x represents a parameter vector, by searching the parameter space of x for the optimal solution. This means that EAs do not operate on a single trial solution, but on a group of solutions, called a population. A solution (called a string) is a vector of all parameters which are to be optimized. After application of evolution inspired operators such as fitness, crossover and mutation, the best solutions are being transformed and saved, forming the next generation, which means that the whole population moves towards better solutions, and finally to the global optimum [11,12,13].

Since the presented problem has two objective functions (minimizing the cost and maximizing the energy efficiency), an appropriate solving method is the multi-objective genetic algorithm because of its ability to locate multiple Pareto optimal solutions in a single run. A solution is said to be Pareto optimal if and only if it is not dominated by any other solution in the performance space. If one solution dominates another, it implies that the first one is non-inferior to the second onefor all the considered performance criteria but it is better than it for at least one criterion. All Pareto solutions form a Pareto front in the performance space.

Although EAs have been proven able to locate promising regions for globaloptima in a search space, they sometimes can have a problem with finding the exact (global) minimum or maximum, especially if the search space is very large. This can be solved by improving the solution obtained by a EA using some other optimization method. In the field of optimization problems, Tabu search (TS) is often used as a ‘higher’ heuristic procedurefor 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 [14].

In this case, mutation operator is replaced by Tabu search module which search neighboring solutions in order to check if there is a better one. Therefore, in every step of the evolution the chromosome with best fitness is selected as Tabu and added to Tabu list. Chromosomes in Tabu list have an aspiration time. In each iteration, aspiration time decreases. When theaspiration time of a given chromosome in Tabu list fall down to zero, that chromosome will be deleted from this list and added to aspiration list. After finding Tabu solution, chromosomes in current population that are similar to it will be are replaced with the chromosome in aspiration list. If the aspiration list is empty, the chromosomes will be replaced with the ones from the last population which have the best (minimal or maximal) fitness value. This increases the diversity of population increase, as well as the search space for the EA, thus avoiding the trap of local optimum.

Energyplus

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. It is usually used by designers for optimizing equipment and insulation features and for evaluating energy consumption depending on chosen materials, shape, construction and orientation. In presented research, it was used to calculate energy consumption for automatically generated solutions (combination of parameters) obtained by the EA.

EXAMPLE

Proposed approach was tested by creating improved EA and merging it with EnergyPlus software in order to find the optimal solution of two conflicting problems: minimizing the cost, expressed by price per m^2 of chosen insulation materials, and maximizing the energy efficiency by minimizing energy consumption. Developed program was tested on the building given in the Exercise 2C from the EnergyPlus database [15]:

Building

Single floor commercial building, rectangular (30.5 m x 15.2 m), divided in five zones, four exterior and one interior, zone height 2.4 m. Exterior zone depth is 3.7 m. The overall building height is 3m. There are windows on all four façades and glass doors on south and north façade. The walls are woodshingle over plywood, R11 insulation, and gypsum board. The roof is covered with artificial gravel mineral board insulation and plywood sheathing. The floor slab is 0.1 m thick, made of heavy concrete. The windows and glass doors are double-paned with argon gap. The window to wall ratio is approximately 0.3. The building orientation is defined by the longer axis running east-west. Floor Area: 463.6 m^2.

Internal characteristics

Lighting is 16 W/ m^2, office equipment is 10.8 W/ m^2, one occupant per 9.3 m^2 of the floor area. Level of infiltration is 25% of air per hour. HVAC: Single-zone unitary with DX cooling and gas heating serving north zone, while the other four zones are served by VAV with hot water reheat, return plenum, chiller, boiler, and tower.

Environment: Belgrade, Serbia

Developed EAincluded three variables: prices of two insulation materials (inner and outer) used for external walls, and orientation angle between longitude axis of the building and the North axis. Database of insulation materials included 10 different materials with their prices (euros per m^2) and thermal resistance (m^2K/W), as shown in Table 1. It should be noticed here that the cost of insulation does not necessarily has to be equivalent of its thermal resistance, but also depends on the other aspects, such as complexity of handling.

Table 1 Prices and thermal resistance of analyzed insulation materials
Tabela 1. Cijene i toplinski otpor analiziranih izolacijskih materijala

№	Price	TR
1 (1)	1.70	1.10
2 (2)	2.35	1.50
3 (3)	2.45	1.53
4 (5, 6)	2.65	2.00
5 (10)	2.75	2.04

№	Price	TR
6 (11)	2.75	2.50
7 (12)	2.80	2.55
8 (14)	3.20	1.20
9 (18)	4.65	2.00
10 (19)	4.70	5.10

Consequently, every solution (chromosome) consists of three genes (variables): one is building orientation (real value between 0 and 360) and the other two are indexes of the inner and outer insulation materials (integer values, as given in Table 1). Objective functions were defined as minimal total cost of insulation (€/m^2) and minimal annual energy consumption (kWh).

Optimal search settings of the EA and TS were determined based on previous experience and by trial and error. The settings of EA are shown in Table 2 while the settings of the RS refinement subroutine are presented in the Table 3.

Table 2 Settings used for EA optimization
Tabela 2. Postavke korištene za EA optimizacije

Setting	Value
Number of generations	100
Population size	50
Elitism	10
Crossover type	Two-point
Crossover probability	0.7
Mutation type	Gaussian distribution with zero mean and standard deviation of 0.4
Mutation probability	0.05
Selection type	Tournament selection
Fitness type	Raw

Table 3 Settings used in the TS module
Tablica 3. Postavke korištene u TS modul

Setting	Value
Stepsize	Random value within interval of ±1%
Tabu list length	20 iterations
Number of iterations without improvement	50

RESULTS AND DISCUSSION

Solutions obtained by the improved EA are presented in the Table 4 which shows non-dominated solutions extracted from the final population of each of 14 runs ordered by the average annual energy consumption. Abbreviations IM and OM are for Inner Material and Outer Material respectively. Orientation angle is given in degrees, annual energy consumption in kWh per year and price in euros per m^2 of the envelope.

Table 4 Solutions obtained by the EA
Tablica 4. Rješenja dobiveni EA

EA – results					
№	IM	OM	Angle	Energy	Price
1	10	10	136.10	61820.5	9.40
2	10	9	136.14	61905.0	9.35
3	10	7	136.15	62070.5	7.50
4	10	4	136.05	62130.0	7.35
5	10	3	135.98	62195.5	7.35
6	10	2	135.92	62198.0	7.05
7	10	1	136.87	62250.0	6.40
8	7	7	135.90	62488.5	5.60
9	7	3	135.84	62855.0	5.25
10	7	1	135.79	62965.5	4.50
11	4	1	135.72	63248.5	4.35
12	3	1	135.61	63662.0	4.15
13	2	1	135.65	63268.5	4.05
14	1	1	135.62	63995.5	3.40

Obtained results Table 4, were also compared with data for the building described at the beginning of the section with orientation angle zero, i.e. aligned with the North axis. For that building, if it would be placed in Belgrade and with no budget-issue demands, annual energy consumption would be 66147.4 kWh per year, which means that the best solution considering energy efficiency and disregarding economic aspect, (solution №1) would result in reduction of around 7 % of consumed energy.

When considering the both objectives, presented results show that proposed EA approach produced 14 non-dominated solutions which all can be considered as optimal regarding different objectives, so it is up to a designer or a decision-maker to choose the one that meets his requirements, demands or constraints at the moment. For example, if he is limited to spending no more than 5.5 euros per $m^2$of the insulation, the best solution considering energy efficiency would be the solution №8 (5.60 €/m^2).

On the other hand, if the descision-maker wants to limit the annual consumption on no more than 63000 kWh per year, solution number №10 (62965.5 kWh, 4.50 €/m^2) would be optimal one.

It should be noticed here that all obtained solutions have approximately equal orientation angle (135.86 ± 0.24), which is logical, because if all outer walls are insulated with the same materials, building orientation becomes totally independent problem.

CONCLUSION

In this paper we have presented multi-objective improved evolutionary algorithm for optimization of insulation cost and annual energy consumption. Experimental evaluation showed that proposed approach obtains satisfying results. Presented example also shows that EA can successfully be combined with the EnergyPlus software and used for optimization of constructional and architectural aspects of a given building considering energy efficiency, providing more solutions and enabling the decision maker to choose the one consistent with his requirements and restrictions.

Further research would include more constructional data, such as polygonal shape of the building, lengths of the walls and angles between them, solutions for higher buildings consisting of more floors, as well as multiple choices of lighting and HVAC equipment and their control parameters.

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