BENEFITS OF OPTIMIZING LOW-RISE BUILDINGS

POGODNOSTI OPTIMIZACIJE NISKIH ZGRADA ZA STANOVANJE

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This research dealt with optimization of environmental performance of low-rise houses. Four different houses were optimized such as a gable-roof house, a hip-roof house, a square-base house, and an L-base house. A multi-objective optimization and Pareto solutions were found in Design Builder software by minimizing both CO_2 emissions and thermal discomfort. Suggested alternative solution combinations were given, and compared to the values prior to the optimization. The results indicated valuable benefits of optimization. It can be concluded that the pitched roof house and the L- base house gave better results than that of other houses. Compared to starting values, the CO_2 emissions were decreased by 27% for the square based house upon optimization, while the L-base house had a decrease of 29%.

Key words: *Design Builder; energy efficiency; thermal comfort; CO_2 emission; optimization.*

Ovo istraživanje orijentisano je na optimizaciju niskih zgrada za stanovanje. Razmatrana su četiri koncepta kuća i to kuće sa krovom na dve i četiri vode i kuće sa osnovom kvadratnog i L oblika. Urađena je višekriterijumska optimizacija i pareto dijagrami u softveru Design Builder. Postignuta rešenja zadovoljavaju kriterijum minimizacije emisije CO_2 i minimizacije termičke neudobnosti. Dobijene su kombinacije alternativnih rešenja i vrednosti emisije CO_2 i termičke neudobnosti upoređene su sa vrednostima pre optimizacije. Rezultati pokazuju da se primenom optimizacije postižu značajni benefiti. Zaključak je da bolje razultate daje kuća sa krovom na četiri vode i sa L osnovom. U odnosu na početne vrednosti smanjenje emisije CO_2 iznosi 27% za kuće sa kvadratnom osnovom po izvršenoj optimizaciji, dok za kuće sa L osnovom smanjenje je oko 29%.

Ključne reči: *Design Builder; energetska efikasnost; termička ugodnost; emisija CO_2; optimizacija*

I. Introduction

Modern research in exploitation of houses was primarily directed towards energy efficiency, thermal comfort (quality) of living, and conservation of environment. This paper examines the ways to create houses of such characteristics.

Researchers worldwide, using various criteria, explored energy efficiency and thermal comfort in buildings. Optimization is an alternative approach to solve problems in energy efficiency, environment conservation, and thermal comfort. Fesanghary et al. [1] used the multi-objective optimization, harmony search algorithm to lower residential building emissions. Liu et al. [2] used particle swarm optimization and Pareto optimal solution for the analysis of costs and CO_2 emissions for a construction project. For optimizing the thermal insulation of buildings, Bojić et al. [3] used Hooke Jeewes algorithm in GenOpt with EnergyPlus software. Soršak et al. [4] did economic optimization of energy efficiency for timber housing. Ferrara et al. [5], Cvetković & Bojić [6], and Diakaki et al. [7] used multi objective optimization to increase energy efficiency in buildings. Asadi et al. [8] also used multi-objective optimization in retrofitting strategies. Diakaki et al. [9] examined the feasibility of utilizing multi objective optimization techniques in energy efficiency measures. Magnier & Haghighat [10] used multi-objective optimization with TRNSYS simulations, genetic algorithm and artificial neural networks in building design to improve energy efficiency and thermal comfort. Wright et al. [11] used multi-criterion genetic algorithm for building thermal design and control optimization. Wang et al. [12] applied multi-objective genetic algorithms to green building lifecycle assessment and cost analysis. Zhang et al. [13] used previous experience from a design optimization competition to show integration of optimization for various building shapes to achieve minimal emissions and cost. All these parameters which were observed can be seen as variables of a multi-criteria optimization.

The motivation for this research comes from a need to define parameters which enhance the quality of low-rise housing exploitation from the aspect of energy efficiency, thermal comfort, and environmental impact. To achieve such results, it is necessary to use software for finding optimal solutions. In this research, a multi-criteria optimization was done by using Design Builder software. As a goal function, a Pareto optimum was set for minimizing CO_2 emissions and the number of discomfort hours on a yearly level. The optimization was performed on four types of houses of approximately the same base area. The investigated houses were houses with gable and hip roof, and that with square and L- base. The used variables are the following: the house orientation from north, the heating type, the window area, the window type, the shading coefficient, and the overhang depth.

II. Problem statement

A. Basic assumptions

This research would determine whether houses with different roof types have the same energy efficiency. Furthermore, the question would be whether houses with the same base area, but different base shape have equal energy efficiency. The paper is based on real house projects, for the research to be directly practically applicable.

Consequently, four houses were studied, of similar base areas. The houses were designed, simulated and optimized by using Design Builder software. The first two houses had different roof types, gable and hip (with square bases). The other two houses had different base shapes, square and L-shaped bases (with hip roofs).

The obtained values were that of energy efficiency, environmental impact (the CO_2 emission), thermal comfort (quality) of living, and design cost. The optimization parameters which influence exploitation of houses are the following: house orientation, heating type, shading coefficient, window area (area of the external walls used by windows), window type, and overhang length.

The building orientation directly influences house characteristics. Due to the daily movement of the sun and depending on the overhang depth, the window area and the roof type, there was an orientation with the best possible characteristics.

The overhang depth represents a parameter which depends on the house orientation, and on the position of the sun during the year. As the angle at which sun rays hit the house in the winter is smaller, the sun rays improve heating through the windows. In the summer, the overhang prevents direct sunlight on the windows, thereby increasing thermal comfort.

The heating systems used as an optimization parameter are the radiator heating with natural ventilation, the radiator heating with mechanical ventilation, the heating with thermo-accumulative electrical heaters, and the ground-source heat pump heating.

The window shading mainly regards the type of window overhang, as well as that of windows. This parameter is regarded as very important since it generally influences the amount of heat emitted outside during the heating season.

The window area depends on the house orientation and the overhang depth, as well as the roof type. This value defines the necessary size of windows to maximize beneficial effects.

The window types for optimization are the aluminum windows with thermal block, the aluminum windows without thermal block, the PVC windows and the wooden lacquered windows.

All these parameters are mutually dependant, and the optimal building requires an optimal solution which varies all these parameters simultaneously.

The basic assumption of optimization was that the optimal values for specific houses can achieve savings in energy consumption, accomplish higher thermal comfort, and be more environmentally friendly. The list of parameters can be expanded, however only these parameters were taken into consideration.

Two houses with different roofing are shown in figure 1. The analyzed houses with gable and hip roofs have the same floor plan, as well as all other materials and systems (installations). The only difference was in the roof type. The total floor areas of these houses were $60m^2$. The space heating was with radiators in combination with natural ventilation, heated by natural gas. The weather conditions were taken for the area of Belgrade. The number of tenants was two. All devices were implemented according to those suggested for a two person residence. The starting orientation was north-south with the entrance is turned south.

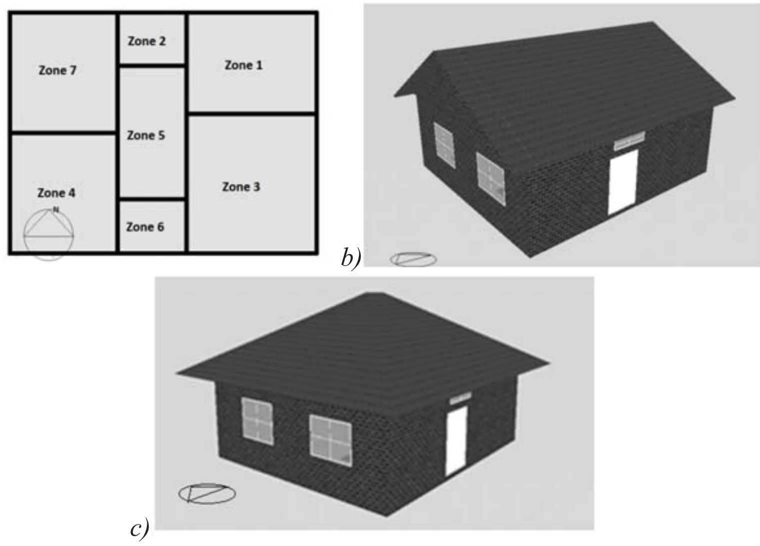

Figure1. Geometric characteristics of the analyzed houses: a) floor plan, b) gable-roof house, c) hip-roof house

The square and L-based houses are shown in figure 2. The base area of each house was $60m^2$*,* as that of the first two houses.

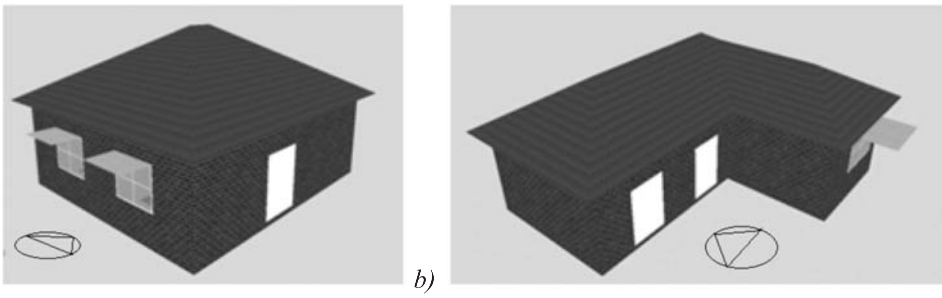

Figure 2. Models of analyzed houses: a) square-base, b) L shape-base

On both houses, an analysis of the heating systems and basic simulations for the whole year were conducted, followed by an optimization of both models.

Both houses were adapted according to the floor plans for a four person family. Both houses had a foyer, bathroom, living room with dining room and kitchen, and two bedrooms. The floor plans are shown in figure 3.

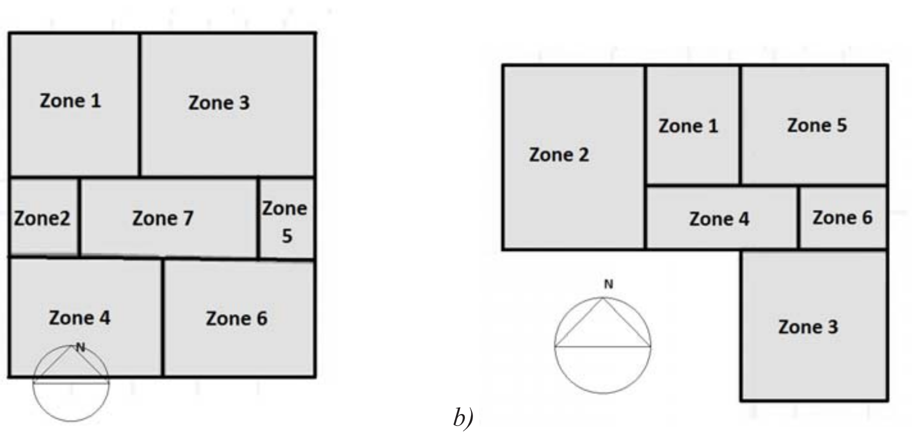

Figure 3. Floor plan a) unit with square base; b) unit with L base

All rooms in both houses with external walls had windows with overhang which prevented excessive heating during the summer.

B. Utilized methods

For calculation, optimization and verification of results Design Builder software was used. The software offers a wide variety of settings of parameters, in order to have this building completely simulate real world conditions and their realistic exploitation. For the calculation of energy use, CO_2 emissions, thermal comfort, achieved temperatures and all other parameters calculations were calculated in Energy Plus software relying on Design Builder.

A multi-criteria Pareto optimization was conducted. Optimization criteria were CO_2 emissions and discomfort. Variables of this optimization were window area, unit orientation, and size of overhang. Design Builder used genetic algorithm for optimization.

Upon completing the optimization, conclusions were drawn based on which the most acceptable model was created. For this model the results of CO_2 emissions, thermal comfort of living and energy use were given and compared. Based on the results themselves a final model with the best possible characteristics was created and analyzed. Results of this model are shown in this paper.

III. Results of optimization

A. Roof type

For the purposes of this analysis a large number of long simulations were conducted, however only the results of the significant ones are given in this paper. The values of the CO_2 emission and the discomfort before the process of optimization for houses with gable and hip roofs are shown in Table 1.

Table 1 –Values of CO_2 emission and discomfort for houses with gable and hip roofs prior to optimization

Roof	Variable name	Value
Gable	CO_2 emission	6569 kg/year
Hip	CO_2 emission	6393 kg/year
Gable	Discomfort	2486 h/year
Hip	Discomfort	2548 h/year

Compared to the initial values, it was found that the house with hip roof had far better characteristics in regard to the CO_2 emissions, while thermal comfort stays approximately the same. It was important to prove this upon completed optimization.

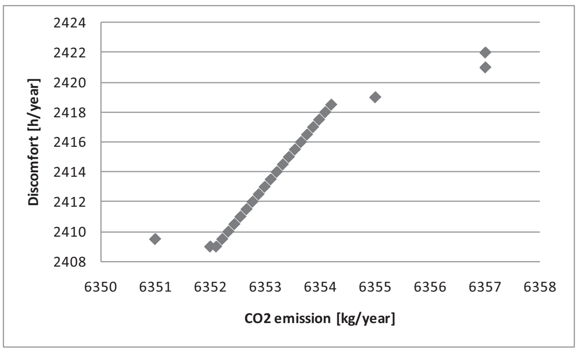

Figure 4. Optimization results for the house with hip roof

For the optimization results for the house with gable roof, the CO_2 emission was in the range of 6569 to 6685 kg/year, while the discomfort ranged from 2486 to 2506 h/year. This means that the most favorable characteristics were in a very small range and that the chosen optimizations did not have a large influence on them. The chosen combination achieved by optimization was 6569 kg/year for the CO_2 emissions and 2486 h/year for the discomfort. For these values, the window area should be reduced to 28% of the external walls, the orientation changed by 43° from the starting position, counterclockwise, and the coefficient which determines overhang to 3.578.

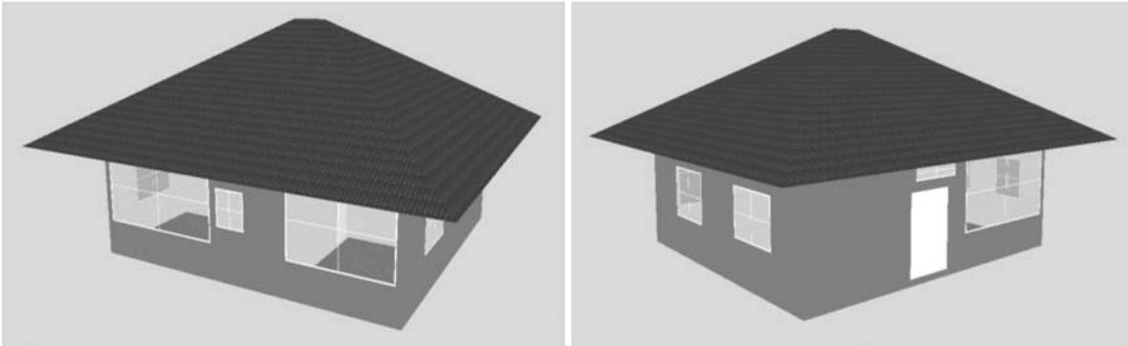

Figure 5 - The optimized houses

The CO_2 emission for the optimized house was 6351 kg/year, while the discomfort was at about 2410 h/year. This case was presented in Fig. 4. In Fig. 5, the optimized houses were presented.

B. Base shape

All calculation and simulation results were presented in Design Builder software. All calculations and simulations were done using Energy Plus in Design Builder. For the optimization with various types of variables, which influences building and its thermal comfort, within Design Builder, a model was made which was optimized by using the genetic algorithm.

1) Previous calculation

The models of both houses had a basic input heating system using thermo-accumulative heaters. This heating used electricity for generating heat. The results of the previous calculation for heating were presented in Table 2.

Table 2 - Previous calculation for heating a square-base and L-base house

	Square-base House			L-base House		
Room name	Thermal comfort tempera-ture [C^0]	Steady state heat loss [kW]	Design capacity [kW]	Thermal comfort tempera-ture [C^0]	Steady state heat loss [kW]	Design capacity [kW]
Hallway	19.60	1.84	2.30	19.22	1.06	1.32
Bathroom	19.68	0.48	0.60	19.59	0.58	0.73
Bedroom 1	19.29	1.69	2.11	18.49	2.48	3.10
Bedroom 2	19.28	1.65	2.06	19.03	1.88	2.35
Living room	19.29	2.33	2.92	18.49	2.97	3.71
Kitchen	19.29	1.72	2.15	19.54	1.16	1.46
	∑	9.71	12.14	∑	10.13	12.67

2) Optimization of heating, shading and window type

To choose between two house types, first, an optimization of both types must be completed. The optimization of both houses was done to determine their maximal energy efficiency according to the choice of the interconnected parameters such as heating system, type of installed windows, coefficient of shading, and window coverage of external walls.

For the house with square-base prior to optimization, the CO_2 emission was 8880 kg/year, and the number of discomfort hours 2559 h/year. For the L-based house prior to optimization, the CO_2 emission was 8806 kg/year, and the discomfort hours 2571 h/year.

Optimization in Design Builder was done by using Genetic algorithm. The optimization gave a Pareto optimum. In the setup of changeable heating systems, there were eight systems taken into account based on radiator heating, floor heating, air heating, etc. For variable types of windows, five types were adopted: aluminum windows, aluminum windows with thermal block, wooden windows, lacquered wooden windows, and PVC windows. Shading coefficient was set from 0 to 1.5, while the coverage of windows was set from 20 to 80%. The objective function was a minimal CO_2 emission and minimal number of discomfort hours during the year. The Pareto optimums are shown in figure 6.

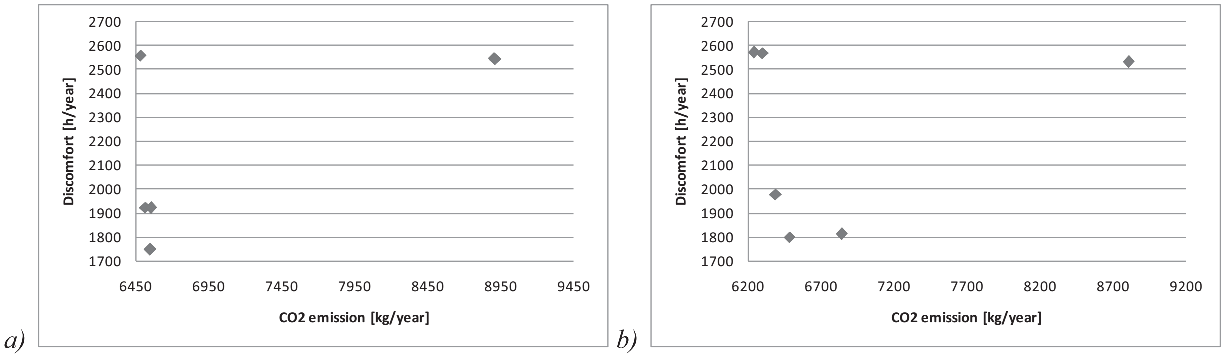

Figure 6 - Pareto optimums: a) square-based house; b) L-based house.

The Pareto optimization of the square-based house showed that the CO_2 emission varied from 6483 kg/year to 8915 kg/year, and the number of discomfort hours varied from 1747 h/year to 2559 h/year. As a The Pareto optimum according to the lowest CO_2 emission of 6483 kg/year with 2559 h/year of discomfort, the following parameters were acquired such as the floor heating with natural ventilation, the window coverage of 42%, the windows with lacquered frames, and the shading coefficient of 0.240.

The Pareto optimization of the L-based house yielded the CO_2 emissions varied from 6242 kg/year to 8808 kg/year. Then, the number of discomfort hours varied from 1799 h/year to 2571 h/year. The Pareto optimum according to the lowest CO_2 emission of 6242 kg/year (2571 h/year of discomfort), the following parameters were acquired such as the floor heating with natural ventilation, window coverage of 59%, shading coefficient of 0.242, and windows with lacquered frames.

3) *Final calculation of energy consumption*

After optimization, the final calculation of energy consumption of the heating system can be performed. The optimal solution for window coverage is different for both houses. The L-based house required greater percentage of the window coverage. The square-based house optimally had the floor heating, which differed from the initially chosen radiator heating. The L-based house utilized the initial heating system. The window type also varied between houses. The lacquered wooden frame windows were found as optimal for the square-based house, while the L-based house optimally had the PVC window frames. The shading coefficient did not vary significantly for both house types. The results of the completed calculation are shown in Table 3.

Table 3 - Final calculation of heating for L and square based houses

	Square House			L House		
Room name	Thermal comfort temperature [C^0]	Steady state heat loss [kW]	Design capacity [kW]	Thermal comfort temperature [C^0]	Steady state heat loss [kW]	Design capacity [kW]
Hallway	19.29	1.86	2.34	19.25	1.05	1.31
Bathroom	19.58	0.49	0.61	19.69	0.57	0.71
Bedroom 1	18.94	1.80	2.25	18.79	2.34	2.92
Bedroom 2	18.93	1.76	2.20	19.23	1.8	2.25
Living room	18.92	2.48	3.10	18.66	2.87	3.59
Kitchen	18.85	1.87	2.34	19.63	1.14	1.42
	∑	10.26	12.84	∑	9.77	12.2

IV. CONCLUSION

The basic conclusion is that there is a realistic possibility of maximizing beneficial, and simultaneously minimizing negative effects in construction and exploitation of low-rise houses. The costs are similar for non-optimal and optimal house, therefore the aspect of cost can be ignored in this research.

The houses attained through optimization had lower CO_2 emissions than the initial houses with gable roof about 3.4%, and hip roof around 0.6%. The houses made by using optimization were better by emission and discomfort criteria from that of house with gable roof by about 3.2%, and from that of house with hip roof by about 5.7%. Due to the decrease in CO_2 emissions, the optimized houses had proportional decrease in energy consumption.

The CO_2 emissions value for the L-based house and square base house are similar prior to optimization. The discomfort hours were almost equal for both houses. The CO_2 emissions for houses with square-base were decreased by 27% after optimization, while the L based house has a decrease of 29% after optimization. The discomfort hours stayed almost equal for both houses. After optimization, the L-based house had about 4% lower CO_2 emissions than that of the square-based house.

From the completed optimizations, it may be concluded that to minimize CO_2 emissions it is better to construct the L-shaped house with hip roof. A big advantage of this house compared to the other three houses, is in the decreased costs for the heating system. In addition, after optimization, the energy consumption of the L-based house was 6% lower than that of the square-based house.

It can be noticed that there was an increase in low-rise house performances through implementing the optimization process in the process of their design. The improvement in its performance was not drastic, however overall characteristics of the house were largely improved. This approach yielded to higher thermal comfort in house and environmental conservation.

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