Multicriterial optimization of the selection of the best measures for energy performances improvement of the multifamily housing in Belgrade

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Abstract: The subject of this paper is multi-criteria analysis of the selection of the best group of measures for energy efficiency improvement of multifamily housing in the suburb Konjarnik in Belgrade, including energy performances improvement of the building envelope and solar thermal systems' application. Results show the selection of the optimal sets of measures for energy efficiency improvement using the method of multi-criteria compromise ranking of alternative solutions - AHP method (Analytical Hierarchical Process). The goal of optimization is to select the best combination of measures for energy renewal of the existing building, or the best variant of a series of offered favorable variants in terms of adopted criteria and defined limitations.

Key Words: decision-making, multi-criteria optimization, measures for improving the energy performance of buildings.

1. Introduction

Many suburban settlements had been built in Belgrade after the World War II. In that time, a few prefabricated systems were mostly in use in our country resulting in housing settlements which consisted of numerous buildings with the same or similar layouts. Belgrade's building stock has a significant number of buildings whose energy performance has to be improved. One of the examples is the housing settlement Konjarnik which has been selected as a case study in which possibilities for improving energy performance are analyzed. The subject of the analyses is typical 8-storey building (ground floor, 6 floors and attic) which consists of 5 lamellas. For the analyses one of the central lamellas is selected (Fig. 1). The building is located in a semi-closed block, on the south oriented hillside. Its longer, east-west axis is parallel to the isohypses. Methodological approach includes the presentation of measures for energy renovation, indication of energy consumption and selection of the optimal sets of measures for energy efficiency improvement using AHP method.

Fig. 1. Location (left) and appearance (right) of the building in Konjarnik settlement

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For the purpose of energy renewal of the existing building and according to recommendations of national regulations, 5 measures for energy efficiency improvement were adopted. The measures include the thermal performances improvement of non-transparent and transparent parts of the thermal envelope of the building and the use of renewable energy sources, respectively integration of solar thermal collectors into the building envelope.

The following measures of energy performance improvement of envelope are selected: increasing the thickness of thermal insulation (on parapet wall and attic slab) including thermal bridges break, completely replacement of the windows by modern one with improved thermal and solar features, and glazing of loggias. Two models (M1 and M2) of building envelope improvement are selected and shown in Table 1.

Table 1. Models of thermal performance improvement of the building envelope

Models of thermal performance improvement	**PARAPET WALL**		**ATTIC SLAB**		**GLAZING**				**Predicted exchanges of the air flow**
					Windows		**Loggias**		
	Wall structure	**U-value [W/m²K]**	**Thickness of thermal insulation**	**U-value [W/m²K]**	**Type of glazing and profiles**	**U-value [W/m²K]**	**Type of glazing and profiles**	**U-value [W/m²K]**	
Model M1	internal concrete 10cm, thermal insulation 5cm, external concrete 5cm + 5cm added expanded polystyrene **total TI thickness = 10cm**	0.371	10cm of added hard mineral wool resulting in 22cm of thermal insulation	0.171	double glazing (4+12+4mm) laid in five-chamber PVC profiles	2.30	double glazing (4+12+4mm) laid in five-chamber PVC profiles	2.30	2 - 3
Model M2	internal concrete 10cm, thermal insulation 5cm, external concrete 5cm + 10cm added expanded polystyrene **total TI thickness = 15cm**	0.255	10cm of added hard mineral wool resulting in 22cm of thermal insulation	0.171	low-emission glazing with argon filler laid in five-chamber PVC profiles	0.90	double glazing (4+12+4mm) laid in five-chamber PVC profiles	2.30	0.8 - 1

Four distinctive variants of position of solar thermal collectors on building envelope are selected and shown in Fig. 2 (Krstić-Furundžić and Kosorić, 2009):

- I Design Variant: solar panels mounted on the roof and tilted at 40˚, area of 100 m^2 (Fig. 2-a),
- II Design Variant: solar panels integrated in parapets (vertical position-90˚), area of 90 m^2 (Fig. 2-b),
- III Design Variant: solar panels integrated in parapets and tilted at 45˚, area of 120 m^2 (Fig. 2-c),
- IV Design Variant: solar panels integrated as sun shadings (horizontal position-0˚), area of 55 m^2 (Fig. 2-d).

Fig. 2. (a) I Design Variant: roof 40˚ (roof and facade layouts), (b) II Design Variant: parapet 90˚, (c) III Design Variant: parapet 45˚ and (d) IV Design Variant: sun shading 0˚

Considering that all of the proposed measures for energy efficiency improvement of the building can be simultaneously applied, 4 combinations of possible measures for each Model (M1 and M2) were adopted and defined as alternatives:

- Model 1/2 + Roof collectors 40°;
- Model 1/2 + Roof collectors 40° and facade collectors 90°;
- Model 1/2 + Roof collectors 40° and facade collectors 45°;
- Model 1/2 + Roof collectors 40° and facade collectors 90° +sun shading 0°.

The combinations of the proposed measures are done on the basis of engineering experience.

2. Theory and Results

Selection of the optimal sets of measures for energy efficiency improvement is made on the basis of multi-criteria optimization using the method of multi-criteria compromise ranking of alternative solutions - AHP method (Analytical Hierarchical Process).

AHP method is one of the most popular methods of scientific analysis of scenarios and decision-making through the process of evaluating alternatives in the hierarchy which consists of goal, criteria, sub-criteria and alternatives. This method is suitable for use in optimization of procedures for the selection of energy renewal measures in the case of more diverse criteria that are often mutually opposed, and a number of alternatives where each alternative can be accurately evaluated according to each criterion. Also, based on the calculation by AHP method, the consistency of decisions is usually achieved and hierarchy of alternatives is clearly defined according to set goal (Pohekar and Ramachandran, 2004).

In this paper the multi-criteria analysis is based on the results of previous research related to energy savings for space heating achieved by improving the building envelope (Krstić-Furundžić et al., 2013), and energy savings for water heating achieved by the application of solar thermal collectors (Krstić-Furundžić and Kosorić, 2009). Indicators of energy savings are obtained through numerical simulation.

2.1 Results of Numerical Simulations

Based on the official data of the Belgrade heating plant energy consumption for heating was estimated, while the electricity consumption for water heating was calculated according to the actual water consumption. The results of all the proposed measures for energy performances improvement of the building envelope were calculated on the basis of thermodynamic simulation of 3D mathematical models in a specialized software package TAS, according to Serbian Regulations on energy efficiency of buildings and Regulations on terms, content and method of issuing certificates of energy performance of buildings.

The results of thermal energy production of the proposed variants of solar thermal systems' application and monthly thermal energy demands satisfaction were calculated on the basis of simulations in the program Polysun 4 (Fig. 3). For the calculation of thermal energy consumption for water heating for households, the real consumption of water was taken into consideration. Thermal energy demands for water heating is calculated regarding number of occupants and hot water consumption per person per day. Consumption of hot water amounts 7,200ℓ (20-50˚C) per day for one block. In terms of energy consumption it is 251 kWh per day, i.e. 91,618.3 kWh per year for one block.

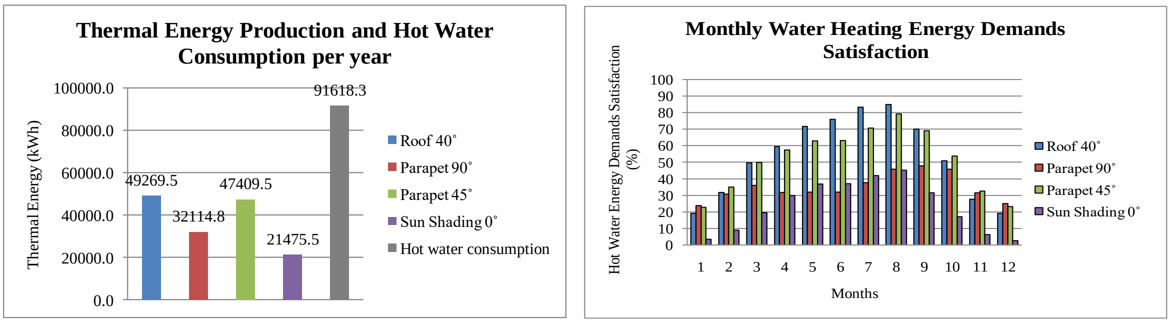

Fig. 3. Thermal energy production and hot water consumption per year (left) and satisfaction of water heating energy demands per months (right)

Eight possible combinations of proposed measures for improving energy efficiency of the building are defined as alternatives. Their contribution to annual energy savings for space and water heating is shown in Tables 2 and 3.

Table 2. Annual energy consumptions and savings for space and water heating for the Model 1 and different variants of STC application (Alternatives 1, 2, 3 and 4)

Alternatives	Model of the building	Annual energy consumption (kWh)			Energy savings (kWh)	Reduction of energy consumption (%)
		For space heating	For hot water	Total		
	Model of the existing building	424.572	91,618	516,190		
1	Model 1 + Roof collectors 40°	44,690	42,349	87,039	429,151	83
2	Model 1 + Roof collectors 40° and facade collectors 90°	44,690	10,234	54,924	461,266	89
3	Model 1 + Roof collectors 40° and facade collectors 45°	44,690	energy surplus (+5,060)	44,690	471,500	91
4	Model 1 + Roof collectors 40° and facade collectors 90° +sun shading 0°	44,690	energy surplus (+11,242)	44,690	471,500	91

Table 3. Annual energy consumptions and savings for space and water heating for the Model 2 and different variants of STC application (Alternatives 5, 6, 7 and 8)

Alternatives	Model of the building	Annual energy consumption (kWh)			Energy savings (kWh)	Reduction of energy consumption (%)
		For space heating	For hot water	Total		
	Model of the existing building	424,572	91,618	516,190		
5	Model 2 + Roof collectors 40°	22,135	42,349	64,484	451,706	88
6	Model 2 + Roof collectors 40° and facade collectors 90°	22,135	10,234	32,369	483,821	94
7	Model 2 + Roof collectors 40° and facade collectors 45°	22,135	energy surplus (+5,060)	22,135	494,055	96
8	Model 2 + Roof collectors 40° and facade collectors 90°+sun shading 0°	22,135	energy surplus (+11,242)	22,135	494,055	96

2.2 Results of Multicriterial Analysis

2.2.1 AHP Method - Analytical Hierarchy Process

AHP - Analytic Hierarchy Process (or Analytical Hierarchy Process) is a mathematical method and represents a strong and flexible decision making technique which helps in setting priorities and reaching optimal decisions in situations when quantitative and qualitative aspects have already been taken into consideration. By reducing complex decision making to comparisons between pairs of alternatives and by synthesizing results, AHP helps not only in decision making but leads to a rational decision and showing the complete order of the importance of alternatives in the model. Created in a way to reflect the way people think, AHP was developed by Professor Thomas Saaty in the 1970s of the last century. Model for multicriteria decision making is usually implemented through the following four phases:

- Structuring of the problem; Goal definition; Defining criteria and alternatives;
- Data collection for alternatives according to defined criteria;
- Analysis of possible alternatives for the goal achievement (relative weights evaluation);
- Selection of the optimal alternative of problem solution.

The first phase - structuring of the problem consists of decomposing a specific complex problem of decision making in series of hierarchy, where each level represents a smaller number of controlled attributes. The graphics of structuring problem that consider selection of the best measures for improvement of energy performances of the multifamily housing in Belgrade is shown in Fig. 4.

The first level of the structure is defining the goal.

The second level of the structure for multi-criteria optimization represents a set of 4 criteria which is adopted and according to which alternatives are evaluated. These four criteria are:

- Annual energy consumption for space and water heating (Criterion C1),
- Annual CO_2 emissions (Criterion C2),
- Investment costs of energy renovation of the building (Criterion C3),
- Return period of investment means (Criteria C4).

The third level implies defining alternatives.

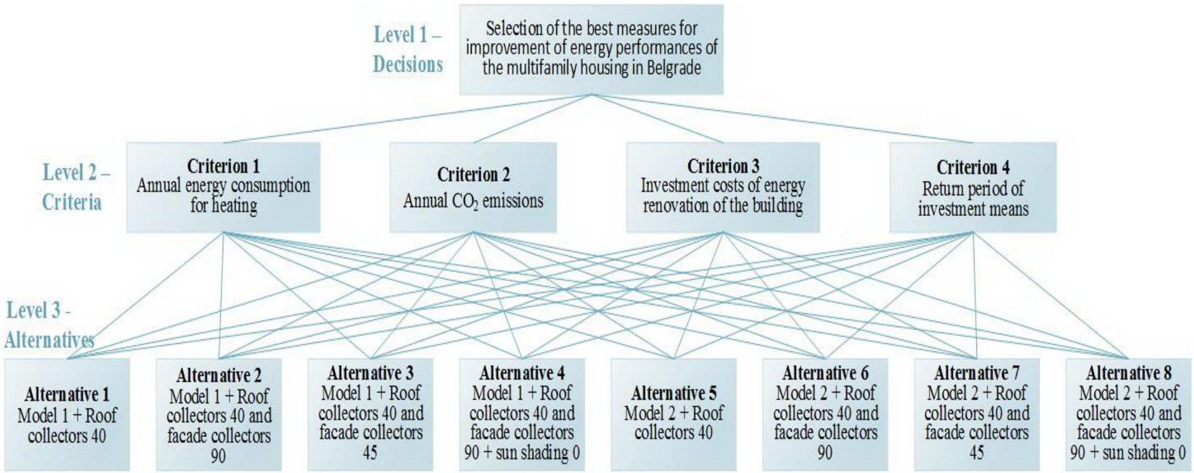

Fig. 4. Structuring of problem of the selection of the best measures for improvement of energy performances of the multifamily housing in Belgrade

The second phase refers to collecting data. Data for alternatives are specified according to defined criteria, as shown in Table 4.

Table 4. Data for alternatives specified according to defined criteria

Alternatives	Model of the building (combinations of proposed measures)	Annual primary energy consumption (kWh)	Annual CO_2 emissions (kg)	Investment costs of energy renovation of the building (€)	Return period of investment means (years)
1	Model 1 + Roof collectors 40°	87,039	34,064	187,180	7.96
2	Model 1 + Roof collectors 40° and facade collectors 90°	54,924	17,043	250,180	9.16
3	Model 1 + Roof collectors 40° and facade collectors 45°	44,690	11,620	271,180	8.55
4	Model 1 + Roof collectors 40° and facade collectors 90° + sun shading 0°	44,690	11,620	288,680	10.34
5	Model 2 + Roof collectors 40°	64,484	28,200	211,910	9.03
6	Model 2 + Roof collectors 40° and facade collectors 90°	32,369	11,179	274,910	10.10
7	Model 2 + Roof collectors 40° and facade collectors 45°	22,135	5,755	295,910	9.35
8	Model 2 + Roof collectors 40° and facade collectors 90° + sun shading 0°	22,135	5,755	313,410	11.25

After data collection, their evaluation is performed in the third phase. By using the Saaty's scale in pairs, the importance is given to the ratio of two criteria when their values are expressed quantitatively, qualitatively and in different measurement units. Saaty's scale is the ratio scale with five intensity degrees and four intermediate stage (Table 5) which corresponds to a value evaluation about how many times one criterion is more important than another. The same scale is used in comparison of two alternatives, but in this case the values are interpreted as an assessment of how many times the higher priority is given to one alternative over another relative to their respective values.

Table 5. Format for pairwise comparisons, according to Saaty's scale

Intensity of importance	Definition	Explication
1	Equal importance	Two criteria or alternatives equally contribute to the objective
3	Moderate importance	Based on experience (estimation), it is given moderate priority to one criteria or alternative over another
5	Strong importance	Based on experience (estimation), it is given strong priority to one criteria or alternative over another
7	Very strong, demonstrated importance	Based on experience (estimation), it is given vary strong priority to one criteria or alternative over another
9	Extreme importance	The evidence on which it is based favors for one criteria or alternative have been confirmed with the highest conviction
2, 4, 6, 8	Intermediate values	

Assessment of the relative weight is also part of the third phase of AHP method implementation. Matrix of pairwise comparisons is converted into the problem of determining their own values in order to obtain their own unique and normalized vectors, as well as the weight of all attributes at each level of the hierarchy, with the weight vector. AHP method is one of the most popular methods due its possibility to identify and analyze the consistency of decision-makers in the process of comparing the elements of the hierarchy (Saaty, 1980). Monitoring the consistency of assessments at any time in the process of comparison of pairs of attributes is performed using the index of consistency:

$$C.I. = (\lambda_{\max} - n)/(n-1) \tag{1}$$

by which the ratio of consistency ($C.R. = C.I./R.I.$) is calculated, where *R.I.* is random index, for which is used table (Table 6) with theoretical values.

Table 6. Values of the random index (Saaty, 1980)

n	1	2	3	4	5	6	7	8	9	10
R.I.	0	0	0.52	0.90	1.11	1.25	1.35	1.40	1.45	1.49

The coefficient λ_{max} is a maximum and main feature of the value of matrix of comparisons, while *n* is size of matrix of comparisons. Assessment of the relative importance of the criteria (priorities of alternatives) is acceptable if $C.R. \leq 0.10$.

One of the major problems in the implementation of this method is to define the attributes of decision-making on the second level (decision making criteria) and evaluation of their relative weight. The authors have defined criteria and assess the value of their relative weights based on their own experience in previous scientific research giving a slight dominance to economic criterion – investment costs (Table 7).

In accordance with the foregoing and considering that the criteria comparison is based on subjective assessment of the decision-maker which requires constant monitoring to ensure the necessary accuracy, the comparison of attributes on the second level (decision making criteria) is carried out by constant checking of their consistency (Table 7).

Table 7. Comparison of attributes on the second level (decision making criteria)

	C1	C2	C3	C4	Weights
C1	1	1	0.5	4	0.2545
C2	1	1	0.5	4	0.2545
C3	2	2	1	3	0.4069
C4	0.25	0.25	0.33	1	0.0842

$\lambda_{max} = 4.231$; $C.I. = 0.0410$; $C.R. = 0.0461 \leq 0.10$

Comparing the alternatives on the third level was enabled by converting the values of all criteria functions shown in Table 4 in values of Saaty's scale. The appropriate matrices of comparing the alternatives on the third level for each attribute (decision making criteria) and their priorities are shown in Table 8. By using MychoiceMydecision software the relative weight of the alternatives in the model is calculated. In order to get rank of the alternatives, all the intensity values were inserted in the software rating model.

Table 8. Matrix of relevant weights of alternatives in relation to the criteria C1-C4

Alternative	Alternative weights in relation to criterion C1	Alternative weights in relation to criterion C2	Alternative weights in relation to criterion C3	Alternative weights in relation to criterion C4
A1	0.0148	0.0178	0.3549	0.3301
A2	0.0497	0.0414	0.1348	0.1181
A3	0.0845	0.1054	0.0699	0.2109
A4	0.0845	0.1054	0.0376	0.0830
A5	0.0280	0.0237	0.2613	0.0888
A6	0.1631	0.1130	0.0826	0.0406
A7	0.2962	0.2967	0.0349	0.1078
A8	0.2793	0.2967	0.0241	0.0207

2.2.2 Selection of the best measures for improvement of energy performances of the multifamily housing in Belgrade

The overall synthesis of the problem of selection the best measures for improvement of energy performances is the forth phase - final procedure implementing AHP (Table 9).

It is carried out in such way that all alternatives are multiplied by the weights of individual decision-making criteria, and the results are summarized.

Table 9. Selection of the optimal alternative

Criteria	Criteria weight	C.weight x A1	C.weight x A2	C.weight x A3	C.weight x A4	C.weight x A5	C.weight x A6	C.weight x A7	C.weight x A8
C1	0.2545	0.0038	0.0126	0.0215	0.0215	0.0071	0.0415	0.0754	0.0711
C2	0.2545	0.0045	0.0105	0.0268	0.0268	0.0060	0.0288	0.0755	0.0755
C3	0.4069	0.1444	10.0549	0.0284	0.0153	0.1063	0.0336	0.0142	0.0098
C4	0.0842	0.0278	0.0099	0.0178	0.0070	0.0755	0.0034	0.0091	0.0017
		0.1805	**0.0880**	**0.0945**	**0.0706**	**0.1270**	**0.1073**	**0.1742**	**0.1581**

3. Conclusion

By accurately procedure implementation of AHP method alternatives ranking was carried out, as shown in Fig. 5. It is estimated that the alternative A1 has the greatest total value of 0.1805, and therefore is the most appropriate or optimal alternative according to determined criteria priorities. Alternative A7 also has slightly lower total value of 0.1742. It can be noted that the best ranked alternative, Alternative 1 is the best individually by two criteria (investment costs and return period of investment means), as well as Alternative 7 (annual energy consumption and CO_2 emissions). The index of consistency is 0.0847, so considering the value less than tolerant limit of 0.1, the result can be considered consistent.

Fig. 5. Alternatives ranking

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