ANALIZA INDIKATORA ENERGETSKE EFIKASNOSTI I OBNOVLJIVIH IZVORA ENERGIJE KOD POSTOJEĆIH ZGRADA

THE ANALYSIS OF ENERGY EFFICIENCY INDICATORS AND RENEWABLE ENERGY SOURCES FOR EXISTING BUILDINGS

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Efikasnost i korišćenje energije i resursa postalo je najvažnije merilo kvaliteta zgrada. Zgrade su u čvrstoj vezi sa tлом, a samim tim i sa prirodom iz koje mogu da crpe svu potrebnu energiju. Cilj je da količina te energije bude što manja. Ulaganje u energetska efikasnost zgrada trebalo bi da bude prioritet, jer je ulaganje u energetska efikasnost, ujedno i ušteda. Izgradnja energetska efikasni zgrada i postrojenja sve više se oslanja na primenu bioklimatskih održivih postulata. Postojeći građevinski fond je daleko veći u odnosu na fond novogradnje, pa se danas energetska efikasni principi ne primenjuju samo kod projektovanja i izgradnje novih objekata, već se aktivno teži i primeni odgovarajućih mera i aktivnosti za unapređenje energetske performansi kod postojećih zgrada. U procesu rekonstrukcije i sanacije izgrađenih objekata, sa aspekta njihove energetske optimizacije, najveća pažnja posvećuje se objektima stambenog karaktera. Kroz ulaganje u materijale za termoizolaciju i korišćenje obnovljivih izvora energije povećava se vrednost zgrade i omogućava se brz povratak uloženi sredstava. Jedan od primarnih ciljeva jeste ušteda potrošnje energije za grejanje i hlađenje uz poboljšanje unutrašnjeg toplotnog komfora i primenu obnovljivih izvora energije. Pri tom je potrebno sagledati veliki broj kriterijuma i faktora koji se tiču rekonstrukcije objekta u pogledu njegovog preprojektovanja, poboljšanja termičke zaštite, kao i uvođenja adekvatnih efikasni, ekoloških i ekonomski isplativih tehničkih sistema koji koriste nekonvencionalne prirodne energetske resurse, i njihovim se vrednovanjem opredeliti za najoptimalnije rešenje. Kod donošenja odluka ovakvog karaktera, višekriterijumska analiza može biti od velikog značaja. Rad istražuje problematiku višekriterijumske analize u domenu unapređenja energetske efikasnosti postojećeg građevinskog fonda, kao i mogućnost odabira optimalnog rešenja primenom metode analitičkih hijerarhijskih procesa (AHP). Cilj rada je da se AHP metodom odrede prioritetni i dominantni faktori unapređenja performansi arhitektonskih objekata, uzimajući u obzir aspekt energetske efikasnosti i uticaj na životnu sredinu, uz odgovarajuću ekonomsku isplativost.

Ključne reči: višekriterijumska analiza; AHP metoda; energetska efikasnost; obnovljivi izvori energije; postojeći objekti

The efficiency and resources use have become the most important measures of buildings quality. The buildings are in contact with the ground and nature of which they can drain necessary energy. The aim is that amount of this energy has to be as small as possible. Investing in energy efficiency of buildings should be a priority, because it represents saving at the same time. The construction of energy-efficient buildings is increasingly relying on the application of bioclimatic sustainable postulates. The existing building stock is higher than new construction fund, so energy efficient principles are not only applied in the construction of new facilities, but also for improving energy performances of existing buildings. In the process of buildings reconstruction, in term of energy optimization, the greatest attention is given to residential buildings. Through investments in thermal insulation materials and use of renewable energy sources, the value of the building increases and a quick return on investment

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is enabled. One of the primary goals is to save energy for heating and cooling, to provide thermal comfort and use renewable energy sources. At the same time, it is necessary to consider a number of criteria related to the building reconstruction in term of redesign, thermal protection as well as the implementation of efficient, ecological and economically viable technical systems, and by its evaluation to define optimal solution. For making these decisions, multi-criteria analysis can be of great importance. The paper examines the problem of multi-criteria analysis in the field of improving energy efficiency of the existing buildings, as well as the possibility of selecting the optimal solution using the method of analytic hierarchy process (AHP). The aim is to identify the dominant factors for improving the performance of architectural buildings, using AHP, taking into account the aspect of energy efficiency with appropriate economic viability.

Key words: multi-criteria analysis; AHP method; energy efficiency; renewable energy sources; existing buildings

1 Introduction

Energy efficiency is one of the basic postulates of nowadays sustainable development, and the minimization of energy consumption required for heating and cooling one of the primary goals of society [1, 2]. Awareness about the consequences of irrational use of conventional non-renewable energy sources and inadequate management of energy and materials, has arisen in the last decades of the XX century, drawing a series of political, economic and urban activities intended to complete and restructure the unsustainable process of buildings construction and exploitation, responsible for the largest share of total energy consumption in the world. The housing sector is the most extensive and today the primary aim is reaching an adequate level of energy efficiency and comfort in facilities intended for family and multi-family housing. The largest number of residential buildings was constructed in the period between the 50s and 80s when the concept of energy efficiency was neglected. As the existing stock of housing facilities is more extensive than the percentage of new construction per year, it is considered that the greatest energy savings can be achieved by revitalizing existing buildings.

The availability of appropriate forms of energy represents an essential factor in achieving a sustainable development of one environment. Countries that strive for this goal, are questioning their energy systems for future energy planning and strategies that are in line with sustainable development goals. The energy aspect of the existing facilities rehabilitation tends to rationalize consumption of energy, conserve building materials along with building life extending, to improve the internal thermal comfort and to use renewable energy sources. Improving energy efficiency includes a series of activities whose ultimate goal is to reduce the consumption of all types of energy in the building, while improving the comfort conditions inside it in accordance with the microclimate conditions of the site. At the same time it is necessary to take into account the various opportunities and methods of energy revitalization that correspond to the residential buildings, and to opt for appropriate measures which will promptly improve the energy performance of building and be economically viable too [3]. Practice shows that the highest energy and financial resources saving can be achieved by energy renovation of the old buildings in the term of improving the thermal characteristics of the building envelope, its reconstruction and rehabilitation, and implementation of appropriate systems which are based on the use of renewable energy sources. Therefore, in the process of buildings revitalization, it is primarily necessary to pay attention to the possibilities of efficient use of existing materials and technical systems for heating, cooling, lighting, ventilation and their improvement, with the inclusion of new materials and systems later.

Reconstruction and renovation of the residential buildings structure include architectural-constructive measures for energy efficiency which are related to the improvement of thermal characteristics of all envelope elements and existing systems for heating, cooling, lighting, ventilation and protection from Sun and wind, as well as to redesigning the building in a functional view [4]. Optimizing the thermal envelope is one of the most important methods of improving the energy performances of existing residential buildings, because it completely eliminates the causes of heat losses. Namely, it is known that the largest amount of accumulated heat in the object is lost by the facade and roof openings and as a result of inadequately designed internal and external thermal barriers of the walls, floors, ceilings and roofs. Therefore, in the process of buildings rehabilitation, the joinery must be restored by replacing the windows of single and double glazing with triple insulated glazing and by providing the

sealing of the windows and exterior doors. In addition, the buildings need to be thermally insulated and it is necessary to prevent the occurrence of „heat bridges“ as localized envelope parts with increased heat loss, by introducing or upgrading the thermal insulation material, preferably at the outer and then in the interior thermal barriers which are located at the junction of heated and unheated areas. The improvement of the buildings thermal insulation properties is performed in accordance with calculated heat transfer coefficient for each of the thermal envelope elements types and prescribed rules [5, 6]. In order to form an adequate thermal mass of the envelope, the replacement of facade, floor, roof coverings and other building elements and materials also occurs in some cases. The existing technical systems improvement means preventing heat losses in the water pipes for supplying the heating bodies, isolating the pipes and introducing the temperature control valves. The reconstructing process, from the aspect of ensuring an adequate level of energy efficiency, also includes the introduction of greenery on roofs and facades of buildings, as well as the application of efficient devices and smart systems for lighting and energy consumption control. Certain savings in energy consumption can be achieved by introducing Sun protection systems that prevent overheating in the summer period, residential spaces redesigning by a windshield introduction in the entrance zone and changing the functional arrangement of rooms in relation to the orientation. In cases where the reconstruction of the thermal envelope, and the improvement of the existing technical systems for heating, cooling, lighting and ventilation are not sufficient measures for improving the energy performances, new technical systems based on the application of renewable energy sources will be implemented [7, 8]. The introduction of passive solar constructions such as greenhouses, dual facade systems, floor heat storages and application of PCM materials in the Tromb's walls, have particularly important role [1, 4, 9]. In addition, significant savings are achieved by using photovoltaic and thermal solar panels, and geothermal probes and collectors as a heating and cooling system in the facility. In some cases, it is possible to ventilate the area using the Vitruvius's effect of air circulation, and heat it using biomass from harvest and wood residues.

Taking into account the large number of mentioned measures, which must be taken into consideration during the process of improving energy performances, the paper deals with problems of multi-criteria decision making and multi-criteria analysis of indicators for the energy revitalization of existing residential buildings, as well as with the possibility to choose the most optimal solution from the aspect of energy efficiency. The aim of the paper is to point out to the importance of multi-criteria analysis use at the moment of making complex and important decisions in the field of energy efficiency. The research is based on the alternatives ranking using the mathematical method of Analytic hierarchy process (AHP).

2 Methodology

For the purpose of ranking energy efficiency indicators in existing residential buildings, the mathematical method of Analytic Hierarchy Process (AHP), which enables solving the complex decision problems, was used. One of the areas of method application is a multi-criteria analysis where, based on a predefined set of indicators and the value of the attributes for each alternative, a selection of the most acceptable solution can be made, with the aim of presenting the final order of all alternatives in the model, according to their importance. Methodologically speaking, the AHP method is a multi-criteria technique based on the spread of a complex problem through a hierarchy, so that the goal of the research is at the top, while the criteria, sub-criteria and alternatives are at lower levels. The AHP method allows interactive creation of problems as preparation of decision-making scenarios, and then evaluation in elements pairs of the hierarchy. After that, according to the strictly determined model, the corresponding weight coefficients of all elements of the hierarchy are determined, whereby the sum of the weight coefficients of the elements at each level of the hierarchy is equal to one (1). This condition allows the decision maker to rank all the elements in a horizontal and vertical sense.

In this paper, alternatives have been evaluated by experts in the field of bioclimatic design and energy efficiency. Any comparison of the two elements of the hierarchy is done using the Saaty's scale [10, 11]:

$$S = \left\{ \frac{1}{9}, \frac{1}{8}, \frac{1}{7}, \frac{1}{6}, \frac{1}{5}, \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, 1, 2, 3, 4, 5, 6, 7, 8, 9 \right\} \quad (1)$$

The priority which one alternative has over another is expressed by descriptive values. Based on the comparison in pairs of hierarchy elements, the appropriate matrix of criteria comparison is formed. The AHP method allows monitoring the consistency of the estimates at any time in the process of comparing the pairs of alternatives by using the indexes:

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \quad CR = \frac{CI}{RI} \quad (2)$$

where: CI is index of consistency, CR is the ratio of the consistency, RI is a random index (consistency index of the matrix), n is the dimension of comparison matrix, $\lambda_{\max}$ is the maximum eigen value of a matrix. If the comparison matrix applies to the $CR < 0.10$ alternatives priorities are counted as acceptable [12, 13, 14].

Table 1: Values of a random index RI

n	1	2	3	4	5	6
RI	0.00	0.00	0.58	0.90	1.12	1.24

3 Results and discussion

The research focuses on the ranking the two main groups of criteria that must be taken into account in the process of improvement the energy performances of existing residential buildings:

A is reconstruction and adaptation of the building;

B is implementation of systems based on the application of renewable energy sources.

The sub-criteria related to the reconstruction and adaptation of the building and the use of renewable energy sources are marked as follows:

A₁- renovation of joinery: A₁₁- glass replacement of windows and doors with appropriate thermal insulating glass; A₁₂- securing windows and door gaps; A₂- improvement of thermal insulation properties of the building: A₂₁- change in type and thickness of thermal insulation material of external thermal barriers (walls, floors, roofs); A₂₂- introduction of thermal insulation in internal barriers of objects oriented to unheated areas (ceilings, floors, walls); A₂₃- change in the type and thickness of other building materials; A₃- improvement of ventilation, lighting, heating and cooling systems: A₃₁- introduction of a valve on heating bodies for heat regulation; A₃₂- introduction of smart systems for controlling heating, cooling, artificial lighting, etc.; A₃₃- introduction of greenery on the roofs and facades of the buildings; A₃₄- use of efficient household devices (including energy-saving light bulbs); A₃₅- isolation of hot water supply pipes in the heating system; A₃₆ - chimney restoration; A₄- introduction of Sun protection systems: A₄₁- use of interior and exterior curtains (blinds, brussels, etc.); A₄₂- planting the high protective greenery in front of the south and west sides of the building; A₅- redesigning: A₅₁- introduction of windshield if it does not exist; A₅₂- change of the arrangement of rooms in relation to the orientation;

B₁- introduction of passive solar systems: B₁₁- introduction of greenhouse as intermediate space for heat storage or double facade systems; B₁₂- use of phase-change materials (PCM) in walls with collector function; B₁₃- introduction of floor heat storage; B₂- introduction of active solar systems: B₂₁- use of roof photovoltaic solar panels; B₂₂- use of roof thermal solar panels; B₃- use of geothermal energy for heating and cooling: B₃₁- use of geothermal probes; B₃₂- use of geothermal collectors; B₄- use of biomass energy for heating: B₄₁- use of wood biomass; B₄₂- use of harvest residues; B₅- use of wind energy for cooling and ventilation: B₅₁ - application of Vitruvie's cooling effect.

In the Table 2 the interdependence of the estimates of two basic groups of criteria is given and a matrix of comparisons based on (1) and (2) is formed. It represents a comparison of criteria at the first level. Table 3 presents a matrix of sub-criterion comparison relating to the reconstruction and adaptation of residential buildings and the corresponding weight coefficients (Wsc). Thus, for example, the renovation of joinery is more important than the application of the sun protection system with the relevant importance 7. Since $CI = 0.048$, the $CR = 0.043 < 0.10$ matrix is consistent.

Table 2: Comparison matrix in relation to the criterion groups A and B

	A	B	Wc
A	1	2	0.6667
B	1/2	1	0.3333

Table 3: Comparison matrix in relation to the criterion group A

A	A ₁	A ₂	A ₃	A ₄	A ₅	Wsc
A ₁	1	2	6	7	9	0.4757
A ₂	1/2	1	5	6	8	0.3289
A ₃	1/6	1/5	1	2	4	0.0973
A ₄	1/7	1/6	1/2	1	3	0.0647
A ₅	1/9	1/8	1/4	1/3	1	0.0334

Table 4 presents a matrix of sub-criteria comparison relating to the implementation of systems based on the application of renewable energy sources, and the weight coefficients (Wsc) are calculated within it. Thus, the introduction of passive solar systems is more important than the application of active solar systems with the relevant importance 2. Since $CI = 0.043$, $CR = 0.038 < 0.10$ the matrix of comparison is consistent. Table 5 obtains the matrix of comparison of the sub-criteria related to the renovation of joinery (A₁) in existing residential buildings and corresponding weight coefficients Wssc. Table 6 shows a comparison of the sub-criteria related to the improvement of the thermal insulation properties of the objects (A₂). The change in thermal insulation in external thermal barriers is of greater importance than the change of other types of building materials in a building with the relevant importance 3. Since $CI = 0.005$, $CR = 0.008 < 0.10$ the matrix of comparison is consistent.

Table 4: Comparison matrix in relation to the criterion group B

B	B ₁	B ₂	B ₃	B ₄	B ₅	Wsc
B ₁	1	2	5	6	8	0.4627
B ₂	1/2	1	4	5	7	0.3141
B ₃	1/5	1/4	1	2	4	0.1121
B ₄	1/6	1/5	1/2	1	3	0.0738
B ₅	1/8	1/7	1/4	1/3	1	0.0373

Table 5: Comparison matrix of subcriteria A₁

A ₁	A ₁₁	A ₁₂	Wssc
A ₁₁	1	2	0.6667
A ₁₂	1/2	1	0.3333

Table 6: Comparison matrix of subcriteria A₂

A ₂	A ₂₁	A ₂₂	A ₂₃	Wssc
A ₂₁	1	2	3	0.5396
A ₂₂	1/2	1	2	0.2970
A ₂₃	1/3	1/2	1	0.1634

In the Table 7, the sub-criteria comparison matrix related to the improvement of ventilation, lighting and heating and cooling systems for existing residential buildings (A₃), as well as corresponding weight coefficients are given. Since $CI = 0.020$, $CR = 0.016 < 0.10$ the matrix of the comparison is consistent. Table 8 shows the matrix of sub-criteria comparison related to the introduction of the Sun protection systems (A₄), while Table 9 shows the sub-criteria matrix comparison in relation to the redesigning of the building interior (A₅).

Table 7: Comparison matrix of subcriteria A_3

A_3	A_{31}	A_{32}	A_{33}	A_{34}	A_{35}	A_{36}	Wssc
A_{31}	1	2	2	3	4	6	0.3432
A_{32}	1/2	1	1	2	3	5	0.2074
A_{33}	1/2	1	1	2	3	5	0.2074
A_{34}	1/3	1/2	1/2	1	2	4	0.1244
A_{35}	1/4	1/3	1/3	1/2	1	3	0.0789
A_{36}	1/6	1/5	1/5	1/4	1/3	1	0.0387

Table 8: Comparison matrix of subcriteria A_4

A_4	A_{41}	A_{42}	Wssc
A_{41}	1	3	0.7500
A_{42}	1/3	1	0.2500

Table 9: Comparison matrix of subcriteria A_5

A_5	A_{51}	A_{52}	Wssc
A_{51}	1	2	0.6667
A_{52}	1/2	1	0.3333

Table 10 presents a matrix of sub-criteria comparison relating to the application of passive solar systems (B_1). Since $CI = 0.009$, $CR = 0.016 < 0.10$ the matrix of the comparison is consistent. Table 11 provides a matrix for the comparison of sub-criteria related to the application of active solar systems (B_2) in existing residential buildings. The both of the tables contain appropriate weight coefficients Wssc.

Table 10: Comparison matrix of subcriteria B_1

B_1	B_{11}	B_{12}	B_{13}	Wssc
B_{11}	1	2	4	0.5584
B_{12}	1/2	1	3	0.3196
B_{13}	1/4	1/3	1	0.1220

Table 11: Comparison matrix of subcriteria B_2

B_2	B_{21}	B_{22}	Wssc
B_{21}	1	2	0.6667
B_{22}	1/2	1	0.3333

Table 12 presents a matrix for the comparison of sub-criteria related to the application of geo-thermal energy for heating and cooling (B_3), and Table 13 matrix of sub-criteria comparison related to the use of biomass for heating (B_4). Table 14 gives a comparison of the sub-criteria concerning the application of wind energy for cooling and ventilation (B_5).

Table 12: Comparison matrix of subcriteria B_3

B_3	B_{31}	B_{32}	Wssc
B_{31}	1	4	0.8000
B_{32}	1/4	1	0.2000

Table 13: Comparison matrix of subcriteria B_4

B_4	B_{41}	B_{42}	Wssc
B_{41}	1	3	0.7500
B_{42}	1/3	1	0.2500

Table 14: Comparison matrix of subcriteria B_5

B_5	B_{51}	Wssc
B_{51}	1	1.0000

4 Conclusion

In the process of improving the energy performances of already constructed buildings we should take into account a number of criteria and choose the most optimal alternatives that will, for a short period of time, enable rapid and profitable recovery of the building in the term of its energy efficiency. In addition to provide a certain level of housing comfort, as one of the basic needs of modern society, it is necessary, in light of the global trend towards sustainable development, to meet those needs in a way that completely, or at least to some extent, preserves energy resources for future generations. In order to find the best solution for enhancing the energy efficiency of residential buildings, the ranking of appropriate indicators, by AHP method of multi-criteria analysis, was performed. The results of indicators ranking are shown in Table 15.

Table 15: The ranking of indicators

Rank	Name of the indicator	Wc	Wsc	Wssc	W
1.	A ₁₁ - windows and doors glass replacing	0.6667	0.4757	0.6667	0.2114
2.	A ₂₁ - change of thermal insulation of external walls, roof and floors	0.6667	0.3289	0.5396	0.1183
3.	A ₁₂ - securing windows and door gaps	0.6667	0.4757	0.3333	0.1057
4.	B ₁₁ - greenhouse introducing	0.3333	0.4627	0.5584	0.0861
5.	B ₂₁ - photovoltaic roof solar panels use	0.3333	0.3141	0.6667	0.0698
6.	A ₂₂ - thermal insulation introduction of internal walls and floors	0.6667	0.3289	0.2970	0.0651
7.	B ₁₂ - use of PCM materials	0.3333	0.4627	0.3196	0.0493
8.	A ₂₃ - change of other building materials	0.6667	0.3289	0.1634	0.0358
9.	B ₂₂ - thermal roof solar panels use	0.3333	0.3141	0.3333	0.0349
10.	A ₄₁ - application of curtains and brisoles	0.6667	0.0647	0.7500	0.0324
11.	B ₃₁ - use of geothermal probes	0.3333	0.1121	0.8000	0.0299
12.	A ₃₁ - introduction of valves for heat control in heating devices	0.6667	0.0973	0.3432	0.0223
13.	B ₁₃ - introduction of floor heat storage	0.3333	0.4627	0.1220	0.0188
14.	B ₄₁ - use of wood biomass for heating	0.3333	0.0738	0.7500	0.0184
15.	A ₅₁ - introduction of windshield	0.6667	0.0334	0.6667	0.0148
16.	A ₃₂ - introduction of smart systems	0.6667	0.0973	0.2074	0.0135
17.	A ₃₃ - introduction of green roof and wall	0.6667	0.0973	0.2074	0.0135
18.	B ₅₁ - application of Vitruvie's effect	0.3333	0.0373	1.000	0.0124
19.	A ₄₂ - planting high vegetation in front of the building	0.6667	0.0647	0.2500	0.0108
20.	A ₃₄ - use of efficient household devices	0.6667	0.0973	0.1244	0.0081
21.	B ₃₂ - use of the geothermal collector	0.3333	0.1121	0.2000	0.0075
22.	A ₅₂ - changing the rooms position in relation to the orientation	0.6667	0.0334	0.3333	0.0074
23.	B ₄₂ - use of harvest residues for heating	0.3333	0.0738	0.2500	0.0061
24.	A ₃₅ - insulation of hot water pipes	0.6667	0.0973	0.0789	0.0051
25.	A ₃₆ - chimney restoration	0.6667	0.0973	0.0387	0.0025

The research shows that the replacement of glass at windows and doors, ensuring their good sealing and replacing and upgrading thermal insulation materials for external thermal barriers play a dominant role, and eliminate the causes of heat loss in the shortest time, improving thermal and energy properties of existing buildings. In addition, it can be noticed that the introduction of greenhouses, double facades, thermal insulation in the internal barriers positioned along the unheated areas of the

attic, basements and stairs, as well as the application of roof photovoltaic solar panels also affect the achievement of higher energy efficiency. The smallest value in improving the energy performances was recognized in the change of a functional layout of the rooms in relation to the orientation, then in the application of harvest residues for heating, the insulation of pipes for the introduction of hot water in the heating system and in the renewal of existing chimney. Research indicates that the proposed method can be successfully applied in the decision making process related to energy recovery and reconstruction of the existing architectural buildings.

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