ENHANCING SUSTAINABLE FACADE DESIGN: A BELGRADE CASE STUDY

Snežana P. MARKOVIĆ[1], Ljubo P. MARKOVIĆ[2], Mirjana J. MILETIĆ[2*], Rada M. RADULOVIĆ[2], Ružica T. BOŽOVIĆ[2]

[1] Specialist Academic Studies, Sustainability and Resilience of the Built Environment, Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, Serbia

[2] Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, Serbia

* Corresponding author; E-mail: mirjana.miletic@pr.ac.rs

This research examines the potential of widespread facade systems to improve energy performance and enhance user comfort in residential buildings. Utilizing Design Builder software (Version 5.0.3.7), the study specifically aimed to reduce heating energy consumption, a significant concern in the climatic conditions of Serbia. The methodology incorporated both technical performance assessments and economic analyses, evaluating the economic viability through metrics such as Return on Investment (ROI), Net present value (NPV), and Internal rate of return (IRR). The multi-criteria evaluation framework employed allowed for a comprehensive analysis, balancing technical performance with economic and qualitative factors to identify the most favorable facade systems. By addressing both the immediate economic returns and longer-term benefits, this research contributes to a more sustainable and economically feasible building practice.

Key words: *glazing systems, facades, residential buildings, energy performance, cost benefit analysis.*

1. Introduction

The urgent need for energy renovation in Serbia's residential sector is driven by pressing ecological, economic, and architectural imperatives. Serbia lags significantly behind European standards in energy efficiency, which is particularly evident in its outdated housing stock. Current data reveal that over 400,000 homes in Serbia lack adequate thermal insulation, leading to an average energy consumption of 220 kWh/m²/year—drastically higher than the European average of 70 kWh/m²/year [1, 2]. This substantial discrepancy underscores the critical necessity for developing a model that not only enhances the thermal properties of Serbian residential buildings but also addresses the broader issues of energy efficiency and internal comfort. Having all that in mind following research questions had occurred:

RQ1: What are the most effective strategies for improving the thermal efficiency of residential buildings in Serbia?

RQ2: How can advanced thermal insulation and glazing systems be integrated into existing buildings to optimize energy efficiency and internal comfort?

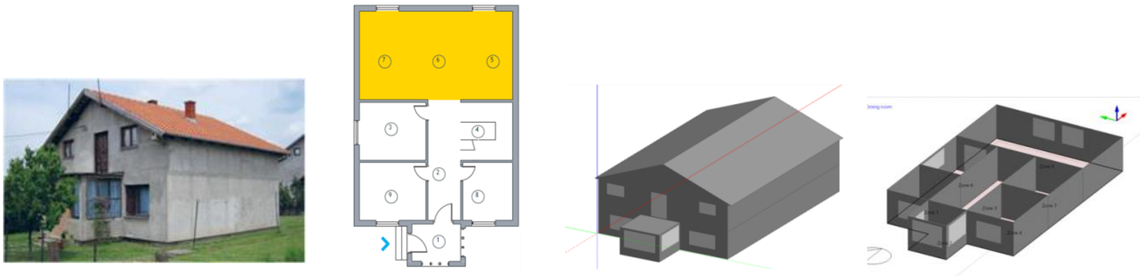
RQ3: What are the ecological and economic benefits of implementing such energy renovation strategies in Serbia's residential sector?

The literature underscores the importance of sustainable architecture and energy-efficient design in achieving global sustainability goals [3]–[9]. Advanced thermal insulation and energy-efficient glazing systems are critical components in this effort, offering substantial energy savings and improved thermal comfort [10]–[14]. In the context of Serbia, energy renovation of residential buildings presents a significant opportunity to reduce environmental impact, lower energy costs, and enhance living conditions [15]–[18]. This literature review highlights the need for a comprehensive approach that integrates advanced materials, design innovations, and aesthetic considerations to create sustainable, energy-efficient buildings.

The theoretical framework guiding this study is rooted in the principles of sustainable architecture and energy-efficient design. The concept of sustainability here is multifaceted, encompassing not only environmental considerations but also economic and social dimensions. By focusing on energy efficiency, the study aligns with the broader global sustainability goals, such as reducing carbon footprints and minimizing energy consumption in the built environment. Central to this theoretical perspective is the notion that buildings are not just static structures but dynamic entities that interact with their environment [19]. The application of advanced thermal insulation in building envelopes—such as facades, roofs, and floors—is a key strategy in reducing energy consumption and associated costs [20]. This approach aligns with theories of passive solar design, which advocate for the use of building orientation, material properties, and design innovations to naturally regulate indoor temperatures [21]. Another crucial aspect of the theoretical framework is the role of energy-efficient glazing systems. Modern glazing technologies, featuring advanced materials and design innovations like thermal insulating glass and high-performance frames, contribute significantly to thermal comfort and energy performance [22]. These systems not only reduce the need for active heating and cooling but also enhance the building's resilience to external environmental factors [23]. Moreover, the architectural integration of these energy-efficient components must strike a balance between aesthetic appeal and functional durability. This balance is essential in creating buildings that are not only energy-efficient but also capable of withstanding adverse weather conditions and mechanical impacts over time [24]. This study seeks to develop a comprehensive approach to energy renovation in Serbia's residential buildings, with a particular focus on improving thermal insulation and glazing systems. By addressing these issues, the research aims to contribute to the broader sustainability goals of reducing environmental impact and energy costs, while simultaneously enhancing the living conditions of Serbian residents.

2. Materials and Methods

To conduct technical and economic analyses on selected facade solutions for energy renovation, a family house with two units in Batajnica, a suburb of Belgrade, was chosen. Built in the 1980s with solid brick construction, this incomplete house typifies residential dwellings in Serbia, constituting 43.86% of the total [25]. Consequently, the findings of the technical-economic analysis conducted in this research can be extrapolated to similar types of family housing units commonly found throughout Serbia.



a) b) c) d)

Figure 1. a, b) Family house in Batajnica, Belgrade, c,d) Model in DesignBuilder software

2. 1. Technical description of the house

The building is a standalone structure, characterized by a unique floor plan measuring 7.9 by 4.4 meters. Adequate openings have been strategically positioned to fulfill the basic requirements for natural lighting and ventilation within individual rooms, while maintaining minimal visual or functional connection with the surrounding terrain or immediate environment. Specifically, a 14 cm thick layer of thermal insulation has been installed between the rafters in the roof structure, supplemented by an additional 10 cm of insulation over the LMT ceiling on the first floor, directed towards the unheated attic space. Although the facade has been plastered, it lacks sufficient thermal insulation (with a thickness of 5 cm). The windows are wooden and feature single glazing, contributing to heat loss. Moreover, there is no thermal insulation in the flooring, although a 2.2cm layer of parquet has been laid over the concrete floor slab. Heating is provided by a wood stove in combination with electricity heating. Consequently, only the living area on both floors is currently heated, forming an independent spatial and functional unit within the structure [25].

2.2 Proposed measures of improvement of energy efficiency of the building

Although unfinished, this facility cannot be improved without major investments and serious interventions. Proposed measures to improve the thermal characteristics include the improvement of façade and replacement of window systems. Façade systems are presented as combination of W1, W2, W3 façade wall (Table 1-3) and P1, P2, P3, P4, P5 and P6 window construction (Table 4). Suggested options include investigation of energy efficiency of:

• the existing facade envelope (cement plaster 0.02m, brick 0.25m, mineral wool 0.05m, and gypsum plaster 0.012m) with the change of window systems that include wooden, PVC or aluminum frames with double or triple low-emission glass with argon filling W1;

• "Demit" façade cladding with a thermal insulation layer of expanded polystyrene d = 10 cm, options include wooden, PVC or aluminum frames with double or triple low-emission glass with argon filling W2;

• "Sandwich" façade envelope with a heat-insulating layer of expanded polystyrene d = 5 cm, an air layer of 3 cm and a façade brick d = 12 cm, and for window systems the options offered include wooden, PVC or aluminum frames with double or triple low emission glasses with argon filling, W3.

Tables (1-3) provide an overview of the technical characteristics of the improved positions of the thermal envelope.

Table 1. Technical characteristics of the existing façade wall W1

Layers	**d(m)**	**λ**	**U (W/m²K)**
Gypsum plaster	0.013	0.85	0.547
Brick wall	0.25	0.61	
Mineral wool	0.05	0.041	
Cement plaster	0.02	0.85	

Table 2. Technical characteristics of the Demit façade W2

Layers	**d(m)**	**λ**	**U (W/m²K)**
Gypsum plaster	0.013	0.85	0.291
Brick wall	0.25	0.61	
Expanded polystirene	0.100	0.035	
Cement plaster	0.02	0.85	

Table 3. Technical characteristics of the ventilated sandwich façade wall W3

Layers	**d(m)**	**λ**	**U (W/m²K)**
Gypsum plaster	0.013	0.85	0.435
Brick wall	0.25	0.61	
Expanded polystirene	0.05	0.035	
Vapour layer	0.005	0.21	
Air	0.01	0.026	
Brickwork outer	0.12	0.76	

Technical characteristics of the proposed windows construction are presented in the Table 4.

Table 4. Window construction

Window construction	**Frame**	**Glass**	**U (W/m²K)**	
			Uf	**Ug**
Window P1	Laminetad wood (d=68 mm) spruce	Double glazing ar (4-float+16+4–low emission glass)	3.633	2.566
Window P2	Laminetad wood (d=68 mm) spruce	Triple glazing ar (4-float+16+16+4–low emission glass)	3.633	1.601
Window P3	PVC five chambered	Double glazing ar (4-float+16+4–low emission glass)	3.476	2.566
Window P4	PVC five chambered	Triple glazing ar (4-float+16+16+4–low emission glass)	3.476	1.601
Window P5	Alluminium with thermal break	Double glass ar (4-float+16+4–low emission)	5.014	2.566
Window P6	Alluminium with thermal break	Triple glazing ar (4-float+16+16+4–low emission glass)	5.014	1.601

The choice of the optimal option will depend on the most favorable ratio of the required investment and the energy savings that the offered option brings.

3. Thermal behavior of the façade systems

The research was carried out using the program DesignBuilder, Version 5.0.3.7. It is a software package for calculating the energy needs, comfort and CFD analysis of all kind of buildings [26].

Table 5. shows the results of the calculation of the thermal behavior of the proposed facade systems.

Table 5. Energy consumption for different façade systems (kW)

Façade / Window construction	Existing façade	Demit façade	Sandwich façade
Existing window construction P0	16517.48		
Window construction P1	15690.30	13191.91	14361.07
Window construction P2	15055.72	12537.91	13900.63
Window construction P3	15686.05	13187.52	14497.44
Window construction P4	15051.74	12533.84	13896.49
Window construction P5	15745.21	13249.54	14557.67
Window construction P6	15107.49	12591.31	13952.47

Table 6. gives an overview of energy saving comparing with the existing situation.

Table 6. Energy saving for different façade systems (kW)

Façade / Window construction	Existing façade	Demit façade	Sandwich façade
Existing window construction P0			
Window construction P1	827.18	3325.57	2156.41
Window construction P2	1461.76	3979.57	2616.85
Window construction P3	831.43	3329.96	2020.04
Window construction P4	1465.74	3983.64	2620.99
Window construction P5	772.27	3267.94	1959.81
Window construction P6	1409.99	3926.17	2565.01

Based on the obtained results shown in table 6., it can be seen that the greatest savings in the amount of energy consumed for heating are realized in the combination of facade cladding 2 - "Demit facade" and window construction P4-PVC five-chamber profile with triple glass (4-float+ 16+4+16+4-low emission) filled with argon.

4. Cost Benefit Analysis

Cost Benefit Analysis (CBA) is among the traditional methods of evaluation based on the analysis of economic (financial) indicators of projects. It evaluates the profitability of projects, thus enabling their prioritization [27].

Although existing manuals for Cost Benefit Analysis may have different definitions of steps, they generally include the following: project context and objectives, project identification, justification of the project and alternative options, financial analysis, economic and risk analysis [28].

Net savings in current costs for each year, which resulted from investments in energy efficiency measures and projects:

$$B = \sum_{t=1}^{n} (B_t * P_e - \Delta C_e) \quad (1)$$

where:

B – total annual savings,

B_t- energy saving for one year ($t = 1$ до n),

P_e – price of energy for one year,

ΔC_e – change of investment costs comparing with situation before changes in the project.

4.1 Role of Cost Benefit Analysis in the Implementation of Measures for Improving Energy Efficiency

The decision on project financing is based on financial indicators, often involving an assessment of the net present value and the internal rate of return. Net present value (NPV) is obtained by subtracting the present value of project revenues from the present value of total project investment costs [29].

$$NPV = \frac{B_0}{(1+d)^0} + \frac{B_1}{(1+d)^1} + \frac{B_2}{(1+d)^2} + \ + \frac{B_n}{(1+d)^n} - PVI \qquad (2)$$

where:

n - the economic lifespan of the project expressed in years,

B - the net inflow of the project in the observed year,

d - discount rate,

PVI - present value of total project investment costs.

A project is profitable when the net present value is greater than zero, meaning that the discounted savings over the economic lifespan of the project exceed the discounted total investments. Otherwise, investing in such a project doesn't make sense.

The internal rate of return is the discount rate at which the present value of savings equals the present value of total project costs, or the discount rate at which the net present value of the project equals zero:

$$\frac{B_0}{(1+d)^0} + \frac{B_1}{(1+d)^1} + \frac{B_2}{(1+d)^2} + \ + \frac{B_n}{(1+d)^n} = PVT \qquad IRR = d \qquad (3)$$

where:

IRR = d - the internal rate of return,

B - the net income in the n-th year,

n - the duration of the project in years.

The internal rate of return (IRR) of a project should be greater or at least equal to the discount rate, which reflects the cost of funds for financing the project [30].

The following initial assumptions have been adopted for Cost benefit:

- the period of works is in 2023,
- the observed period of this analysis is from 2024 to 2074, that is, the period of exploitation is 50 years,
- the analysis was performed in constant fixed prices in 2023,
- discount year is 3.5%,
- investment costs include all costs for financing, i.e. equipment and construction,
- maintenance depends on external influences and changes in the state of the facade and window systems during the analysis period.

4.2 Data for Cost Benefit Analysis

Cost-benefit analysis plays a crucial role in implementing measures to enhance energy efficiency by considering the financial implications of such measures. While various approaches can improve energy efficiency, it's essential to weigh the financial effects of these initiatives.

When calculating investment costs, price lists of equipment and materials that are current on the market were used. Investments costs of the façade envelope systems and window constructions are given in the Table 7.

Table 7. Investments costs of facades

Facades	Unit	Quantity	Total price (€)
Existing facade	m^2	349.16	0
„Demit facade"			3782.57
„Sendwich" facade			10474.80

Investments costs of the façade envelope systems and window constructions are given in the Table 8.

Table 8. Investments costs of façades and window constructions

Windows	Existing façade (€)	„Demit" façade (€)	„Sendwich" façade (€)
Window construction P1	5335.50	9118.07	15810.30
Window construction P2	**5691.20**	**9473.77**	16166.00
Window construction P3	3734.85	7517.42	14209.65
Window construction P4	**3912.70**	**7695.27**	14387.50
Window construction P5	6402.60	10185.17	16877.40
Window construction P6	6936.15	10718.72	17410.95

The greatest savings in the amount of energy consumed for heating are achieved for facade systems:

• combination of facade envelope 2 - "Demit facade" and window construction P2 - glued laminated wood (d=68 mm) - spruce with triple glass (4 - float+16+4+16+4 - low emission) filled with argon and

• combination of facade cladding 2 - "Demit facade" and window construction P4 - PVC five-chamber profile with triple glass (4 - float+16+4+16+4 - low emission) filled with argon.

Cost benefit analysis was applied for two alternative solutions of window constructions (wood and PVC) in combination with all three offered facade coverings.

Based on the official data of the EDB (Electricity Distribution Serbia, Belgrade) the calculation of the total financial savings of energy, which is achieved by creating the planned facade systems, was made. The calculation results are presented in Table 9, where Ht signify the high tariff (kW) and Lt signify the low tariff (kW).

Table 9. Total financial saving of heating energy obtained by making façade systems (façade envelopes and windows)

	Consumpt. zones	Total energy saving (kW) Existing façade		Demit façade		Sendwich façade		Total financial saving (€) Existing façade	Demit façade	Sendwich façade
		H_T	L_T	H_T	L_T	H_T	L_T			
Window construction P2	Green zone (14%)	97.45	48.72	65.31	132.64	174.46	87.22	6.54	17.80	11.70
	Blue zone (50%)	487.26	243.60	1326.53	663.20	872.29	436.10	49.00	133.46	87.76
	Red zone (36%)	389.80	194.88	1061.22	530.56	697.83	348.88	78.44	213.54	140.42
	Σ	**1461.76**		**3979.57**		**2616.85**				
	Σ (€)							**133.98**	**364.80**	**239.88**
Window construction P4	Green zone (14%)	97.72	48.85	265.58	132.77	174.73	87.36	6.55	17.81	11.72
	Blue zone (50%)	488.58	244.27	1327.89	663.87	873.67	436.79	49.16	133.60	87.90
	Red zone (36%)	390.87	195.41	1062.31	531.10	698.93	349.43	78.65	213.76	140.64
	Σ	**1465.74**		**3983.64**		**2620.99**				
	Σ (€)							**134.36**	**365.17**	**240.26**

4.3 Scenario Analysis for Cost Benefit Analysis

The work execution scenario was analyzed, which includes the following financial indicators:

- Return on Investment - ROI;
- Net present value - NPV;
- Internal rate of return - IRR.

The results of the analysis are presented in tables 12. The indicators of the financial analysis for the window construction P2 are negative and show that the investment is not profitable for any of the facade envelope alternatives offered. The ROI index shows that the investment return period for the demit facade is the shortest and amounts to 25.32 years, while it is significantly longer for the other facade envelopes. The NPV values for all three alternatives are negative, and the IRR for all three alternatives is lower than the adopted discount rate of 3.5%. From this it can be concluded that this combination of improving the facade system is unprofitable.

Table 10. Cost benefit analysis results for the façade system (window construction P4 and facade envelope)

	Façade	Discount (%)	Investment value (Iu) (€)	Net saving (B) (€)	Simple return(ROI) (ann.)	Net present value (NPV)	Internal rate of return (IRR) (%)
Window construction P2	Existing	3.50	5691.20	137.43	41.41	-2467.10	1.20
	„Demit“	3.50	9473.77	374.15	25.32	-660.21	3.05
	„Sendwich“	3.50	16166.00	260.03	65.71	-10394.14	-6.20
Window construction P4	Existing	3.50	3912.70	137.81	28.39	-688.53	2.21
	„Demit“	3.50	7695.27	374.54	20.55	1082.38	4.19
	„Sendwich“	3.50	14387.50	246.42	58.39	-8615.57	-5.20

For window construction P4, financial analysis indicators indicate the profitability of the "Demit Facade" alternative, where the internal rate of return (IRR) is 4.19% and is higher than the discount rate (d =3.5%), and the net present value NPV > 0 (NPV = €1082.38). For this combination of facade system (window construction P4 – “Demit facade”) the ROI index indicates that the payback period is 20.55 years, whereas for other combinations of window constructions and facade cladding, it is significantly longer.

5. Multi-criteria evaluation

Multi-criteria analysis and evaluation, often referring to multi-attribute evaluation, involves selecting and ranking solutions from a set of options in a discrete decision-making space. This paper uses the term "multi-criteria evaluation" to mean multi-attribute evaluation, which also encompasses multi-objective evaluation.

Multi-criteria evaluation is both a problem-solving approach and a collection of techniques aimed at ranking alternatives from most to least favorable [31]. Alternatives differ in how well they meet the objectives of selected criteria, and it is unlikely that one option will be the best in all aspects. Often, goals and criteria conflict with each other.

Common multi-criteria evaluation methods include SAW, AHP, TOPSIS, ELECTRE, PROMETHEE GAIA, MAVT, and VIKOR [32]. This paper will utilize the VIKOR method for the evaluation process.

The VIKOR method (Multi criteria COmpromise Ranking), along with the VIKOR software package, solves optimization problems with multiple heterogeneous and conflicting criteria. The obtained solution is a compromise, which can be either unique or represent a set of close solutions. A compromise solution is a feasible solution that is closest to the ideal solution. This can be especially useful in situations where ideal solutions are not possible and a compromise needs to be made between the available alternatives. The ideal solution is determined based on the best criterion values and is usually not found within the given set of alternative solutions [33]. VIKOR uses relative differences between alternatives to assess how much each alternative deviates from the ideal solution.

The result of the VIKOR method includes ranking lists (based on measures QR, Q for v=0.5, and QS), as well as a compromise alternative or a set of compromise solutions. These results serve as the basis for decision-making and the adoption of the most favorable (multi-criteria optimal) solution [34]. VIKOR can be effective in situations where quick ranking of alternatives and identification of a compromise solution is needed without the complex calculations characteristic of some other multi-criteria analysis methods.

In contrast to VIKOR, many methods such as AHP and TOPSIS use different approaches such as weighting criteria or ranking alternative solutions relative to ideal points. Methods like MAUT (Multi-Attribute Utility Theory) may use absolute values and often focus more on aggregating utility or costs rather than compromise. The VIKOR method can integrate criterion weights into its model to adjust the importance of different criteria when evaluating alternatives. Methods like ELECTRE (Elimination Et Choix Traduisant la Réalité) also use weights but often in different ways, such as eliminating alternatives that do not meet minimum criteria.

5.1 Evaluation of offered alternative solutions of facade systems using the VIKOR method

For the application of the method, Table 11. has generated 18 alternative solutions for façade systems - facade cladding (3) and window constructions (6), which are presented in Chapter 2.2.

Table 11. Offered alternative solutions

Windows	Existing façade	"Demit" façade	"Sendwich" façade
Window construction P1	A11	A21	A31
Window construction P2	A12	A22	A32
Window construction P3	A13	A23	A33
Window construction P4	A14	A24	A34
Window construction P5	A15	A25	A35
Window construction P6	A16	A26	A36

During the selection of the optimal variant of the proposed façade system solutions, evaluation criteria were defined and elaborated through appropriate indicators. Table 12. presents the evaluation criteria and indicators.

Table 12. Selected criteria and corresponding indicators

Criteria	Ext.	Indicators
Construction investment costs (€)	min.	The amount of invested funds for the construction of the facade system (facade cladding + window system)
Energy saving (€)	max.	Monetary equivalent of energy savings for heating
Return on Investment (year)	max.	The time period required to recover the invested funds through achieved energy savings
Maintenance cost	min.	The number of maintenance cycles as recommended by the manufacturer
Durability (year)	max.	The time period provided by the manufacturer for the installed components of the façade system
Aesthetic effect	max.	Rating (1-10) by respondents on the aesthetic appearance of the offered façade system

For determining the relative weights of the criteria, a simplified Delphi method [35], was applied on a sample of 15 respondents (civil engineers, architects). During the determination of the relative weights of the criteria, the respondents were presented with three scenarios. For each of the presented scenarios, the respondents defined weight coefficients, which represent the numerical reflection of the importance of the criteria, as follows:

- The decision maker gives the highest priority to the economic effects - the second and third criteria, then the fourth and first, and criteria five and six are equally less significant ($\omega1=0.12$ **$\omega2= \omega3= 0.30$**; $\omega4= 0.20$; $\omega5= \omega6 = 0.04$);
- When deciding, the decision maker gives priority to the economic effects - the third criterion, taking into account the aesthetic effect, so he also gives priority to the sixth criterion, then the second, fourth and fifth, while the first criterion is less significant (**$\omega3= \omega6= 0.25$** ; $\omega2= \omega4= \omega5=0.15$; $\omega1=0.05$).
- For the decision maker, all criteria have equal importance, so their weights are equal (**$\omega1=\omega2=\omega3=.. = \omega6 =0.1666$**).

For the indicator values, the numerical values presented in the previous chapters were used. For the criteria—construction costs and return on investment, the values shown in Table 10 were used; for the criterion—energy savings, the values from Table 9 were used; while for the criteria—maintenance costs and durability, data provided by the manufacturers were used. The criterion—aesthetic effect is represented by a descriptive rating (1-10) and depends on the impression of the respondents who participated in the Delphi method. Numerical values of the selected criteria and corresponding indicators are given in the Table 13.

Table 13. Numerical values of offered solutions

Alternatives	Investment value (€)	Energy saving (€)	Return on Investment (year)	Maintenance cost	Durability (year)	Aesthetic 1-10
A11	5335.50	77.77	68.61	3	50	10
A12	5691.20	137.43	41.41	3	50	10
A13	3734.85	78.17	47.78	3	50	10
A14	3912.70	137.80	28.39	3	50	10
A15	6402.60	72.61	88.18	3	50	10
A16	6936.15	132.56	52.32	3	50	10
A21	9118.07	312.66	29.16	0.001	100	5
A22	9473.77	374.15	25.32	0.001	100	5
A23	7517.42	307.24	24.01	0.001	100	5
A24	7695.27	369.13	20.55	0.001	100	5
A25	10185.17	202.74	33.15	0.001	100	5
A26	10718.72	246.03	29.04	0.001	100	5
A31	15810.30	189.92	77.98	0.001	200	8.5
A32	16166.00	246.03	65.71	0.001	200	8.5
A33	14209.65	189.92	74.82	0.001	200	8.5
A34	14387.50	246.42	58.39	0.001	200	8.5
A35	16877.40	184.26	91.60	0.001	200	8.5
A36	17410.95	241.16	72.20	0.001	200	8.5

5.2. Discussion of the results of VIKOR method

5.2.1 Scenario 1

Based on the established methodology, comparative presentation of criteria and indicators with appropriate relative weights using the VIKOR method, the following results were obtained - ranking list of alternative solutions according to the QR-minimax strategy; Q - compromise and QS - majority benefit (Table 14):

Extreme indexes 0. 1. 0. 0. 1. 1.

Weight values : ω_1= 0.12 ω_2=0.30 ω_3= 0.30 ω_4=0.20 ω_5=0.04 ω_6= 0.04

Table 14. Results of multi criteria ranking QR, Q and QS

Ranking list		
QR	**Q**	**QS**
A24 0.400	A24 0.000	A24 0.101
A22 0.050	A22 0.045	A22 0.138
A23 0.061	A26 0.092	A26 0.176
A26 0.061	A23 0.092	A23 0.176
A21 0.061	A21 0.120	A21 0.061
A25 0.067	A25 0.154	A25 0.243
A34 0.160	A34 0.419	A34 0.393
A32 0.191	A32 0.505	A32 0.439
A16 0.218	A16 0.583	A16 0.483

A33	0.229	A33	0.627	A14	0.510
A14	0.235	A14	0.632	A33	0.516
A12	0.236	A31	0.660	A31	0.531
A16	0.240	A12	0.688	A12	0.581
A31	0.242	A16	0.744	A35	0.616
A13	0.295	A35	0.819	A16	0.649
A11	0.295	A13	0.916	A13	0.649
A15	0.300	A11	0.916	A11	0.752
A35	0.300	A15	1.000	A15	0.849

Based on the results of the evaluation using the VIKOR method based on the presented criteria and the ranking list according to QR, Q and QS measures (Table 16), it can be concluded that the alternative solution is the facade system A24 - window construction P4 (PVC five-chamber frame with three-layer glass filled with argon) and facade "Demit" casing is the most favorable solution. The advantage of the alternative solution A24 in relation to the first following alternative solution A22 is 0.045 (4.5%).

5.2.2 Scenario 2

Based on the established methodology, comparative presentation of criteria and indicators with appropriate relative weights using the VIKOR method, the following results were obtained - ranking list of alternative solutions according to the QR-minimax strategy; Q - compromise and QS - majority benefit (Table 15.):

Extreme indexes 0. 1. 0. 0. 1. 1.

Weight values : ω_1=0.05 ω_2= 0.15 ω_3= 0.25 ω_4= 0.15 ω_5=0.15 ω_6=0.25

Table 15. Results of multi criteria ranking QR, Q and QS

Ranking list					
QR		Q		QS	
A34	0.133	A34	0.000	A34	0.311
A12	0.150	A32	0.141	A32	0.343
A13	0.150	A14	0.264	A24	0.364
A14	0.150	A36	0.267	A36	0.373
A16	0.150	A33	0.335	A22	0.388
A32	0.159	A12	0.343	A33	0.396
A11	0.169	A31	0.390	A23	0.407
A36	0.182	A13	0.410	A31	0.407
A33	0.191	A16	0.411	A26	0.408
A31	0.202	A24	0.498	A21	0.431
A15	0.238	A22	0.533	A14	0.446
A21	0.250	A23	0.561	A25	0.451
A22	0.250	A26	0.563	A35	0.468
A23	0.250	A21	0.598	A12	0.498
A24	0.250	A11	0.598	A13	0.543
A25	0.250	A25	0.629	A16	0.544
A26	0.250	A35	0.653	A11	0.622
A35	0.250	A15	0.957	A15	0.698

Based on the results of the evaluation using the VIKOR method based on the presented criteria and the ranking list according to QR, Q and QS measures (table 16), it can be concluded that the alternative solution is the facade system A34 - window construction P4 (PVC five-chamber frame with three-layer glass filled with argon) and facade "Sandwich facade" envelope is the most favorable solution. The advantage of the alternative solution A34 has a stable advantage compared to the first following alternative solution A32 and is 0.141 (14.1 %).

5.2.3 Scenario 3

Based on the established methodology, comparative presentation of criteria and indicators with appropriate relative weights using the VIKOR method, the following results were obtained - ranking list of alternative solutions according to the QR-minimax strategy; Q - compromise and QS - majority benefit (Table 16.):

Extreme indexes 0. 1. 0. 0. 1. 1.

Weight values: ω_1=ω_2= ω_3= ω_4= ω_5= ω_6=0.16666

Table 16. Results of multi criteria ranking QR, Q and QS

Range list QR	Range list Q	Range list QS
A33 0.128	A34 0.044	A24 0.326
A34 0.130	A33 0.129	A34 0.339
A31 0.147	A32 0.338	A22 0.359
A32 0.151	A31 0.369	A23 0.366
A11 0.167	A24 0.417	A32 0.378
A12 0.167	A22 0.470	A26 0.386
A13 0.167	A23 0.480	A21 0.398
A14 0.167	A26 0.512	A33 0.407
A15 0.167	A21 0.531	A36 0.411
A16 0.167	A36 0.553	A25 0.423
A21 0.167	A25 0.572	A31 0.427
A22 0.167	A35 0.666	A35 0.482
A23 0.167	A14 0.670	A14 0.485
A24 0.167	A12 0.754	A12 0.537
A25 0.167	A13 0.792	A13 0.561
A26 0.167	A16 0.823	A16 0.580
A35 0.167	A11 0.901	A11 0.629
A36 0.167	A15 1.000	A15 0.691

Based on the results of the evaluation using the VIKOR method based on the presented criteria and the ranking list according to QR, Q and QS measures (table 17), it can be concluded that the alternative solution is the facade system A34 - window construction P4 (PVC five-chamber frame with three-layer glass filled with argon) and facade "Sandwich facade" envelope is the most favorable solution. The advantage of the alternative solution A34 has a stable advantage compared to the first following alternative solution A33 - window construction P3 covering is 0.085 (8.5%).

6. Conclusions

To address the research questions and provide a summary of the paper the following findings have been reached related with the most effective strategies for improving thermal efficiency (RQ1). It is well known that these strategies are crucial in minimizing heat loss during winter and reducing the energy demand of buildings. The paper proposes practical measures for integrating advanced thermal insulation and glazing systems into existing buildings. High-quality, properly installed windows with advanced glazing technologies significantly reduce heat transmission and ventilation losses (RQ2). Implementing the proposed energy renovation strategies offers significant ecological and economic benefits. Ecologically, the reduction in energy consumption leads to lower greenhouse gas emissions, contributing to Serbia's sustainability goals. Economically, the decreased energy demand translates to lower heating costs for residents, offering long-term financial savings (RQ3). This paper proposes practical architectural measures to significantly improve the thermal properties of buildings, focusing on enhancing reducing winter heating costs [31]. Key elements of the thermal envelope causing heat loss were identified, with facade glazing areas replacement being particularly effective, in order to reduce energy demand of buildings through compliance with envelopes thermal property regulations [36]. It is well known that high-quality, properly installed windows can significantly reduce heat transmission and ventilation losses. This paper addresses specific data related to these benefits. Glass is a key material in modern architecture, offering significant technological advancements. Proper selection of glass can greatly enhance building energy efficiency. Various facade and window combinations were analyzed using Design Builder software to identify the best solution for improving energy performance in typical family houses in Belgrade. A detailed simulation and analysis were conducted to evaluate the impact of proposed changes on building performance. This was followed by a cost-benefit analysis to assess the financial viability of the proposed solutions. For the two proposed facade construction solutions, key financial indicator (Return on Investment (ROI), Net Present Value (NPV), and Internal Rate of Return (IRR)) were analyzed.

The results indicate the viability of the alternative solution involving a PVC five-chamber profile with triple glazing and a "Demit facade." This solution has an IRR of 4.19%, exceeding the discount rate of 3.5%, and a positive NPV of 1082.38 €. The ROI is 20.55 years for this combination of facade system improvements. In contrast, the second alternative (window construction with laminated glued wood and triple glazing filled with argon) yielded negative financial indicators, with a significantly longer payback period. This clearly indicates that the second project is not financially viable and not currently a profitable investment. Despite the benefits, the lengthy payback period may deter potential investors, highlighting the need for state incentives to promote energy efficiency investments. It's crucial to consider both monetary and non-monetary factors in decision-making, and methodologies like multi-criteria evaluation can facilitate comprehensive assessments. Using the VIKOR method, alternative solutions were evaluated across three scenarios: (I) prioritizing economic effects; (II) considering both economic and aesthetic effects; and (III) giving all criteria equal weight. The results showed that in the first scenario, the A24 solution (PVC five-chamber frame with triple glazing filled with argon and a "Demit façade") outperformed the next best option, a wooden frame with laminated glued wood and the same facade, by 0.045 (4.5%). In the second scenario, the A34 solution (PVC five-chamber frame with triple glazing filled with argon and a "Sandwich façade") showed a significant advantage over the A32 solution (wooden frame with laminated glued wood, triple glazing filled with argon, and a "Sandwich façade") by 0.141 (14.1%). In the third scenario, A34 also outperformed A33 (PVC five-chamber frame with double glazing filled with argon and a "Sandwich façade") by 0.085 (8.5%). Considering both the Cost-Benefit and VIKOR analyses, the optimal solution is a PVC five-chamber frame with triple glazing filled with argon and a "Demit façade". This solution offers the best balance of energy performance and financial viability in the values provided by given calculations.

International Energy Agency (IEA) reports that improving energy efficiency in buildings could reduce global CO_2 emissions by up to 40% by 2040 . This is particularly relevant in the context of residential buildings, which account for a significant portion of energy consumption worldwide. The focus on energy efficiency and this kind of glazing replacement aims towards achieving these goals and is not only an environmental imperative but also an economic strategy, as it leads to substantial cost savings over the life cycle of buildings [37].

In conclusion, the paper underscores the importance of a comprehensive approach to energy renovation, focusing on practical architectural solutions that enhance the thermal properties of buildings while delivering ecological and economic advantages. By adopting a holistic approach to energy renovation, this research will contribute to the development of more sustainable built environments, aligning with global efforts to combat climate change and promote resource efficiency. As a proposal for future research the findings will be particularly valuable for regions with different climate conditions facing significant challenges in terms of energy consumption, economic constraints, and environmental degradation.

Nomenclature

λ - thermal conductivity coefficient [W/mK]
U- thermal transmittance [W/m^2K]
Uf - U value of the frame [W/m^2K]
Ug - U value of the glass [W/m^2K]
Ht - high tariff [KW]
Lt - Low tariff [KW]

Acknowledgement

Auttors would like to thank Erasmus+ project of the European Commission entitled *Creating the Network of Knoweladge Labs for Susteainable end Resilient Enviroments – KLABS* (No 561675). Article is a part of the research study from the Specialist Study Sustainaibility and Resilience of the Built Environment from the Faculty of Technical Sciences.

References

[1] Azizi, S., Nair, G., & Olofsson, T., Adoption of energy efficiency measures in renovation of single-family houses: A comparative approach. *Energies*, 13(22) (2020), 6042. doi: 10.3390/EN13226042.
[2] Kosanović, S., Miletić, M., & Marković, L., Energy refurbishment of family houses in Serbia in line with the principles of circular economy. *Sustainability*, 13(10) (2021), 5463. doi: 10.3390/SU13105463
[3] P. Sassi, "Strategies for sustainable architecture," *Strateg. Sustain. Archit.*, pp. 1–305, Sep. 2006, doi: 10.4324/9780203480106/STRATEGIES-SUSTAINABLE-ARCHITECTURE-PAOLA-SASSI/ACCESSIBILITY-INFORMATION.
[4] M. Keitsch, "Sustainable Architecture, Design and Housing," *Sustain. Dev.*, vol. 20, no. 3, pp. 141–145, May 2012, doi: 10.1002/SD.1530.
[5] J. Pohl, "Sustainable Architecture Concepts and Principles," *Build. Sci.*, pp. 225–258, Feb. 2011, doi: 10.1002/9781444392333.CH12.
[6] M. L. Maddaus, W. O. Maddaus, M. Torre, and R. Harris, "Innovative water conservation supports sustainable housing development," *J. / Am. Water Work. Assoc.*, vol. 100, no. 5, 2008,

doi: 10.1002/J.1551-8833.2008.TB09634.X.
[7] J. Pohl, "Building Science: Concepts and Application," *Build. Sci. Concepts Appl.*, May 2011, doi: 10.1002/9781444392333.
[8] L. Mitchell and E. Burton, "Neighbourhoods for life: Designing dementia-friendly outdoor environments," *Qual. Ageing Older Adults*, vol. 7, no. 1, pp. 26–33, 2006, doi: 10.1108/14717794200600005.
[9] W. R. Moomaw, R. R. Bhandary, L. Kuhl, and P. Verkooijen, "Sustainable Development Diplomacy: Diagnostics for the Negotiation and Implementation of Sustainable Development," *Glob. Policy*, vol. 8, no. 1, pp. 73–81, Feb. 2017, doi: 10.1111/1758-5899.12350.
[10] U. Schulz *et al.*, "Some recent trends in research and technology of advanced thermal barrier coatings," *Aerosp. Sci. Technol.*, vol. 7, no. 1, pp. 73–80, Jan. 2003, doi: 10.1016/S1270-9638(02)00003-2.
[11] S. T. Nguyen, J. Feng, S. K. Ng, J. P. W. Wong, V. B. C. Tan, and H. M. Duong, "Advanced thermal insulation and absorption properties of recycled cellulose aerogels," *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 445, pp. 128–134, Mar. 2014, doi: 10.1016/J.COLSURFA.2014.01.015.
[12] F. Hu, S. Wu, and Y. Sun, "Hollow-Structured Materials for Thermal Insulation," *Adv. Mater.*, vol. 31, no. 38, p. 1801001, Sep. 2019, doi: 10.1002/ADMA.201801001.
[13] E. Cuce and S. B. Riffat, "A state-of-the-art review on innovative glazing technologies," *Renew. Sustain. Energy Rev.*, vol. 41, pp. 695–714, 2015, doi: 10.1016/J.RSER.2014.08.084.
[14] J. Huang, S. Wang, F. Teng, and W. Feng, "Thermal performance optimization of envelope in the energy-saving renovation of existing residential buildings," *Energy Build.*, vol. 247, p. 111103, Sep. 2021, doi: 10.1016/J.ENBUILD.2021.111103.
[15] M. Brown, "Innovative energy-efficiency policies: An international review," *Wiley Interdiscip. Rev. Energy Environ.*, vol. 4, no. 1, pp. 1–25, Jan. 2015, doi: 10.1002/WENE.125.
[16] L. M. López-Ochoa, J. Las-Heras-Casas, L. M. López-González, and C. García-Lozano, "Energy Renovation of Residential Buildings in Cold Mediterranean Zones Using Optimized Thermal Envelope Insulation Thicknesses: The Case of Spain," *Sustain. 2020, Vol. 12, Page 2287*, vol. 12, no. 6, p. 2287, Mar. 2020, doi: 10.3390/SU12062287.
[17] M. Ferreira, M. Almeida, and A. Rodrigues, "Cost-optimal energy efficiency levels are the first step in achieving cost effective renovation in residential buildings with a nearly-zero energy target," *Energy Build.*, vol. 133, pp. 724–737, Dec. 2016, doi: 10.1016/J.ENBUILD.2016.10.017.
[18] P. Bertoldi, M. Economidou, V. Palermo, B. Boza-Kiss, and V. Todeschi, "How to finance energy renovation of residential buildings: Review of current and emerging financing instruments in the EU," *Wiley Interdiscip. Rev. Energy Environ.*, vol. 10, no. 1, p. e384, Jan. 2021, doi: 10.1002/WENE.384.
[19] M. Achintha, "Sustainability of glass in construction," *Sustain. Constr. Mater.*, pp. 79–104, Jan. 2016, doi: 10.1016/B978-0-08-100370-1.00005-6.
[20] J. X. Lu and C. S. Poon, "Recycling of waste glass in construction materials," *New Trends Eco-efficient Recycl. Concr.*, pp. 153–167, Jan. 2018, doi: 10.1016/B978-0-08-102480-5.00006-3.
[21] S. Stevanović, "Optimization of passive solar design strategies: A review," *Renew. Sustain. Energy Rev.*, vol. 25, pp. 177–196, Sep. 2013, doi: 10.1016/J.RSER.2013.04.028.
[22] K. S. Grewal, C. Hachem-Vermette, and S. Yadav, "Decision-making method to prioritize and implement solar strategies on neighborhood level," *Energy Reports*, vol. 12, pp. 2062–2076, Dec. 2024, doi: 10.1016/J.EGYR.2024.08.009.
[23] A. K. Athieniti and M. Santamouris, "Thermal analysis and design of passive solar buildings," *Therm. Anal. Des. Passiv. Sol. Build.*, p. 296, Jan. 2013, doi: 10.4324/9781315074351/THERMAL-ANALYSIS-DESIGN-PASSIVE-SOLAR-BUILDINGS-AK-ATHIENITIS-SANTAMOURIS.
[24] S. Ghazi and K. Ip, "The effect of weather conditions on the efficiency of PV panels in the southeast of UK," *Renew. Energy*, vol. 69, pp. 50–59, Sep. 2014, doi: 10.1016/J.RENENE.2014.03.018.
[25] Jovanović Popović, M., Ignjatović, D., Radivojević, A., Rajčić, A., Djukanović, Lj., Ćuković Ignjatović, N., & Nedić, M. *Atlas porodičnih kuća Srbije*. Beograd (2012), Arhitektonski fakultet Univerziteta u Beogradu
[26] Pawar, B. S., & Kanade, G. N., Energy optimization of building using Design Builder software. *International Journal of New Technology and Research*, 4(1), (2018).

[27] Mouter, N., et al., Comparing cost-benefit analysis and multi-criteria analysis. In *Advances in Transport Policy and Planning* (2020), (Vol. 6, pp. 225–254). Academic Press. doi: 10.1016/BS.ATPP.2020.07.009.
[28] Mishan, E. J., & Quah, E., *Cost-Benefit Analysis* (6th ed.). Routledge, (2020) doi: 10.4324/9781351029780.
[29] Ekardt, F., Cost-benefit analysis without convincing theoretical basis. In *Economic Evaluation, Cost-Benefit Analysis, Economic Ethics, Environmental Humanities: Transformation, Governance, Ethics, Law*. Springer, Cham. (2022), doi: 10.1007/978-3-030-99284-2_5.
[30] Elariane, S. A., & Dubé, J., Is smart housing a good deal? An answer based on Monte Carlo net present value analysis. *Sustainability*, (2019), 11(15), 4193. doi: 10.3390/su11154193.
[31] Kan, I., Pintelon, L., & Martin, H., The application of multicriteria decision analysis methods in health care: A literature review. *Medical Decision Making*, (2022), 42(2), 262-274. doi: 10.1177/0272989X211019040.
[32] Todorović, M., & Rajčić, A., *Priručnik za energetsku sertifikaciju zgrada - Vodič za investiture, izvođače i projektante*. Beograd (2017), Mašinski fakultet Univerziteta u Beogradu.
[33] Marković, Lj., Cvetković, M., Milić Marković, Lj. (2013). Multi-Criteria Decision-Making when Choosing Variant Solution of Highway Route at the Level of Preliminary Design, FACTA UNIVERSITATIS Series Architecture and Civil Engineering, 11 (1), 71-87.
[34] Opricović, S., Tzeng, G.,H. (2007): Extended VIKOR method in comparison with outranking, *European Journal of Operational Research* 178 (2), 514-529.).
[35] ****, Делпхи метода - шта је то, дефиниција и концепт | Речник 2024* (no date). Available at: https://sr.economy-pedia.com/11038201-delphi-method (Accessed: 26 August 2024).
[36] Harmathy, N., Analysis of smart building solutions for optimizing the energy. *Thermal Science*, (2022), 26(4A), 3119-3132.
[37] “International Energy Outlook 2016 With Projections to 2040 (Technical Report) | OSTI.GOV.” https://www.osti.gov/biblio/1296780 (accessed Sep. 03, 2024).

Submitted: 20.05.2024.
Revised: 03.09.2024.
Accepted: 05.09.2024.