Article

Energy Refurbishment of Family Houses in Serbia in Line with the Principles of Circular Economy

Saja Kosanović 1, Mirjana Miletić 1,∗ and Ljubo Marković 2

1 Department of Architecture, Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, Kneza Miloša Street 7, 38220 Kosovska Mitrovica, Serbia; saja.kosanovic@pr.ac.rs
2 Department of Civil Engineering, Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, Kneza Miloša Street 7, 38220 Kosovska Mitrovica, Serbia; ljubo.markovic@pr.ac.rs
* Correspondence: mirjana.miletic@pr.ac.rs; Tel.: +381-63-8584697

Abstract: To achieve material efficiency, the ongoing initiative to improve thermal properties of family houses in the Republic of Serbia should include harmonization with internationally established and nationally adjusted principles of circular economy. The overall aim of this study was to propose a methodology for optimal decision making between alternative materials and components for energy refurbishment of façades in existing family houses. Together with developed criteria, and their belonging indicators, the methodology was tested on selected case study houses located in the central zone of the city of Belgrade. Using the VIKOR method, five suggested scenarios and three sub-scenarios for façade thermal upgrades were assessed against five determined types of criteria: Economic Cost, Function, Circularity Features, Appearance, and Innovativeness. Obtained results—ranking lists of proposed scenarios—indicate that the optimal solution for energy refurbishment of façades in existing houses could include polyurethane insulation material in combination with the wooden window frames and low-E insulation glass. In future research, it will be necessary to introduce an additional assessment criterion related to the ecological quality of proposed scenarios, as the study revealed that a gap between circularity-related quality, and ecological sustainability, of building materials could be significant.

Keywords: family houses; Serbia; energy efficiency; circularity principles; building materials and components; multi-criteria assessment; optimization

1. Introduction

Circularity is becoming an increasingly relevant issue in education, science, technology, and business. As the success in application of circularity principles largely depends on external entities (stakeholders and actors), the approach is best known under the expression ‘circular economy.’ Numerous business models and strategies for circular economy have been developed internationally [1], especially over the last decade.

Circular schemes aim to ensure growth in accordance with the goals of sustainable development [2,3]. More specifically, to design out waste and pollution, keep products in use, and regenerate natural systems [4]. However, circularity-related topics are equally studied in a narrow sense, by abbreviating product’s ecological impacts in life cycle phases and excluding the detailed considerations of ecological implications of problems and solutions [5]. In the construction sector, circular economy basically strives to achieve the efficiency of building materials by reducing their use and maximizing their closed loops [6]. To that end, different circular models concerning production, supply, installation, modes of use and maintenance, and the end-of-life scenarios for building materials and components have been introduced. Here, the family housing sector comes to the fore, having regarded its significant share in the use of material resources [7] as well as the potential for achieving the material efficiency [8–10].
To this time, only the Rulebook on Detailed Conditions, Criteria and Procedure for Obtaining the Right to Use the Eco-Label; Elements, Appearance and Manner of Using the Eco-Label for Products and Services [11] deals (in a qualitative way) with the circularity-related issues of building materials produced on the territory of the Republic of Serbia. In a broad context, the first national document that specifically uses the term circular economy has been developed in 2020. This Roadmap for Circular Economy in Serbia provides guidelines to involve various actors in an open dialogue and joint creation of solutions for an efficient and fast transition from a linear to a circular economy [12]. In February 2021, the Ministry of Mining and Energetics of the Republic of Serbia launched a new national initiative to enhance, by economic support, the energy refurbishment of family houses [13]. By integrating the principles of circular economy into energy refurbishment, the material efficiency, the reduction in embodied energy, as well as the reduction in exergy dissipation [14] could be achieved together with the operational energy savings. To that end, the overall aim of this research is to define a methodology by which the decisions compatible with the principles of circular economy could be brought in the process of energy refurbishment of family houses in the Republic of Serbia.

2. Theoretical Background
2.1. Circularity Principles and Research Boundaries

Circularity concept in architecture and construction extends from material, to component, to whole building scales. Accordingly, the definition of circularity principles that could be applied in building design and construction must be adjusted to the characteristics of materials and components (building layers [15]), or buildings as a whole. Another significant peculiarity refers to whether these principles are applicable to a newly designed or an already existing structure that is subjected to refurbishment. In this research, the scope of application of circularity principles corresponds to the thermal upgrade of façades of existing family houses, thereby encompassing thermal insulation materials and window components.

Specific interpretation of universal circularity principles, in the case of energy refurbishment of façades of existing family houses in Serbia, is given in the Table 1.

Table 1. Principles of circular economy and their applicability to the elements of thermal upgrade of façades of existing family houses in Serbia.

| Circularity Principle | Applicability in the Case of Façade Thermal Upgrade |
|-----------------------|---------------------------------------------------|
| CP1 Circular Supply   | Recycled content/fully recycled materials; Reclaimed/secondary materials and components |
| CP2 Decreased Material Use | Lightweight materials; Materials with reduced volume mass; Materials exempted from finishing |
| CP3 (De)construction Waste Reduction | Prefabricated, standard, recyclable and easy to (dis)assemble materials and components |
| CP4 Long-lasting Use | Durable, long-lasting and resilient materials and components |
| CP5 Easy Repair and Maintenance | Material and components easy to maintain, repair and (dis)assemble; Modular (de)installation |
| CP6 Upgrade | Materials/components allowing for upgrade during the use |
| - Sharing | An innovation on national scale |
| - Product as a Service | An innovation on national scale |
| CP7 Reselling | Widely applicable, long-lasting and high-quality materials/components |
| CP8 Reuse | Components and materials that are resilient, long-lasting, allowing for disassembly, minor restauaration and the adaptation |
| CP9 Recycling | Separable, recyclable materials; Pure and safe material content |
| CP10 Recovery | Bio-based, biodegradable materials |
2.2. Multi-Criteria Assessment Method

Multi-criteria assessment is a method useful to any decision-making process where a multitude (of mutually opposing) criteria exist. For that reason, multi-criteria assessment also is an efficient, scientifically-based [16] tool to solve conflicts and manage different opinions and standpoints [17]. Nowadays, it is largely supported by computer and communication technologies [18] used in all stages of selection and ranking of different variant solutions.

In this research, multi-criteria evaluation has been adopted as a suitable methodological means to combine energy efficiency demands with the principles of circular economy and other general refurbishment-related requirements, so to obtain the optimal solution under certain given conditions. The process of systemic analysis of different proposed variants of façade thermal upgrades at family houses in Serbia corresponds to the generally prescribed procedure [19] and consists of six phases: (1) Forming the criteria i.e., the sets of criteria; (2) Introducing criteria values and the modes of optimization (desired minimal or maximal values); (3) Defining the weight of criteria; (4) Selecting a method and executing the multi-criteria assessment based on that method; (5) Ranking the variants and identifying the most appropriate variant solution; (6) Possible redefining of criteria weight. As the phases 1–3 and 5–6 are without the significant need to clarify theoretical settings, they are described in chapters 3 and 4 of this study, directly on selected case examples. On the other hand, the phase 4—execution of multicriteria assessment—requires a more detailed description of the method selected for this purpose due to its complexity. To perform multi-criteria assessment of different variants of façade thermal upgrade, method VIKOR—Višekriterijumska optimizacija i KOmpromisno Rešenje (Eng. Multi-criteria Optimization and Compromise Solution) has been selected.

VIKOR Method

Next to TOPSIS, ELECTRE, and PROMETHEE GAIA, VIKOR is a method commonly used in decision-making resulting from many heterogeneous and conflicting criteria. The method is especially suitable for situations where criteria of quantitative nature prevail.

VIKOR was developed by prof. dr. Serafim Opricović from the University of Belgrade—Faculty of Civil Engineering, using as a basis the elements from compromise programming. Opricović presented the basic ideas of VIKOR in his doctoral dissertation in 1979, and the paper published in 2004 [20] contributed to VIKOR becoming a widely recognizable method. In 2009, this paper was identified as the most cited work in the field of economics and business [21].

The method starts from ‘boundary’ forms of Lp-metric [22]. For comparison, the TOPSIS method introduces two reference points, using vector normalization, but it does not consider the relative importance of the distances from these points. Ranking by PROMETHEE, with a linear preference function, gives the same results as ranking by VIKOR, with measure S representing ‘group utility.’ Results by ELECTRE, with linear ‘surrogate’ criterion functions, are relatively similar to the results obtained by VIKOR [23]. Taking into account these facts, as well as the availability of the computer program and the familiarity with its functioning, the final choice for multicriteria analysis in this research was the VIKOR method.

A solution obtained using the VIKOR method is a compromise; it can be unique, or it can represent a set of close solutions. A compromise solution is an acceptable solution that is the closest to the ideal. The ideal solution is determined on the basis of the best values of the criteria. Usually, ideal solution is not contained within a given set of alternative solutions [18].

Working algorithm of VIKOR reads as follows:

The task is to rank alternative solutions \( a_1, a_2, ..., a_j \) for given values of criteria-based functions \( f_{ij}, i = 1, n \) and \( j = 1, J \), where \( n \) represents the number of criteria, and \( J \) the number of alternatives. Ranking procedure is the following [23]:
(A)

For all criteria-based functions \( i = 1, 2, ..., n \), the best \( f^*_j \) and the weakest \( f^-_j \) values are determined according to:

\[
\begin{align*}
    f^*_j &= \max_{(j)} f_{ij} \quad \text{if } i^{th} \text{ function represents a gain} \\
    f^-_j &= \min_{(j)} f_{ij} \quad \text{if } i^{th} \text{ function represents a loss}
\end{align*}
\]

(B)

Based on \( S_j \) and \( R_j \) measures, alternative solutions are ranked, and the position of alternative \( a_i \) in ranking lists \( s(a_j) \) and \( r(a_j) \) determined. Values \( S_j \) and \( R_j, j = 1, 2, ..., J \) are calculated using the relations:

\[
S_j = \sum_{i=1,0} \omega_i \left( f^*_j - f^-_j \right) / \left( f^*_j - f^-_j \right), \text{ for } p = 1
\]

\[
R_j = \max_{(i)} \omega_i \left( f^*_j - f^-_j \right) / \left( f^*_j - f^-_j \right), \text{ for } p = \infty
\]

In relations (3) and (4), \( n \) represents the number of criteria; \( \omega_i \) is the weight of the \( i^{th} \) criterion, and it expresses the preference of the decision-maker i.e., the relative criterion significance; \( S_j \) is the measure of distance \( R(F,1) \) from ideal point to alternative \( j \); \( R_j \) the measure of distance \( R(F, \infty) \) from ideal point to alternative \( j \).

The ranking based on measures \( S_j \) and \( R_j \) results in two ranking lists of alternatives. To obtain a unified ranking list, the compromise programming is applied. Accordingly, \( S_j \) and \( R_j \) now became the criteria-based functions. The new ranking measure is [23]:

\[
Q_j = v Q^S_j + (1 - v) Q^R_j = v \left( (S_j - S^*)/(S^* - S^*) \right) + (1 - v) \left( (R_j - R^*)/(R^* - R^*) \right)
\]

(C)

The best multi-criteria alternative is the one that is in the first position on the compromise ranking list for \( v = 0.5 \), only if there exist [23]:

(C1) ‘Sufficient advantage’ over the alternative from the next position. To assess this ‘advantage,’ the difference between measures \( Q_j \) is used. Alternative \( a' \) has a sufficient advantage over the next alternative \( a'' \) from the ranking list when:

\[
Q(a'') - Q(a') \geq DQ
\]

\( DQ \) represents the ‘advantage threshold.’ For cases with a small number of alternatives, this threshold is limited to 0.25;

(C2) ‘Sufficiently stable’ first position in relation to the change of the weight \( v \) (for \( v = 0.25 \) and \( v = 0.75 \)). Alternative \( a' \) has to be best ranked based on \( QS \) and/or \( QR \) as well.

If any condition is not met, a set of compromise solutions, consisting of the first and the first next alternative, is being formed. If the first alternative does not meet only the condition C2, then only the second from the compromise ranking list enters the set of compromise solutions. If the first-ranked alternative does not meet the condition C1, then the set of compromise solutions contains alternatives from the compromise ranking list all to the alternative that meets the requirement by which the first-ranked does not have a sufficient advantage over that alternative [23].

The results of VIKOR method are ranking lists made according to the measures \( QR, Q \) (for \( v = 0.5 \)) and \( QS \), and a compromise alternative or a set of compromise solutions. These
results represent the basis for deciding and adopting the most favorable (multi-criteria-optimal) solution [23].

If none of the proposed alternative solutions are proven as the most favorable for given weighting coefficients, it is necessary to additionally check how the rank of proposed alternative solutions relates to different weighting coefficients and to determine a stable interval. Here, the Spearman’s rank correlation coefficient is used to examine rank correlations [24]. This coefficient allows us to determine which weight coefficients, i.e., criteria deviate from other solutions the most. That way, a stable interval representing the basis for correcting the initial weighting coefficients can be formed. A stable interval reveals those rank orders that are associated with a strong correlation analysis (where the Spearman’s correlation result is greater than 0.85).

3. Material and Methods

The characteristics of materialization of houses in Serbia primarily depend on the period of their construction [2,7,25,26]. Over the first half of the 20th century, the most commonly used construction materials were ‘čerpić’ (a mix of mud and straw), wood and solid clay bricks, often in combination with natural stone. Floor/ceiling structure was mainly made of wooden beams interfiled with ‘čerpić’ or other dry mixtures; from below, it was covered with straw material, and from the upper side with wooden planks that, in fact, represented the floor finishing layer. Floor on the ground story was covered with stone tiles or left in rammed earth material which often was the case in rural houses. Roof cover consisted of traditional small-sized clay elements (the so-called ‘čeramida’), or larger wooden or stone shingles. Walls and ceilings were covered with lime mortar and then painted with lime-based paints. Doors and window frames were made of wood and, more rarely, of iron.

Solid brick became dominant construction material during the 1950s. Starting from the 1970s, however, it gradually became substituted for prefabricated hollow clay elements of larger dimensions, which shortened construction time, reduced the economic price, but also decreased the thickness of envelope walls. At the same time, traditional roof cover became substituted for prefabricated, larger clay elements, while the main wooden roof structure until today remained the same.

The use of concrete material in the construction of houses in Serbia was modest until the 1970s. From this period, until today, concrete basically represents a support to the massive house structure. It is being used in the form of on-site made horizontal and vertical column- and beam-like elements, foundations, floor/ceiling structures, and staircases.

In today’s practice, walls and ceilings are mostly covered with cement or lime plaster made on the spot or with prefabricated gypsum cardboard panels. Floors and walls are covered with various prefabricated ceramic, wood, or wood-based materials.

Over time, windows were first transformed from single-fold wooden to double wooden with single glass, and then into more complex single wooden frames with thermal insulation glass; during the past two decades, however, polyvinylchloride (PVC) has become dominant material for windows and doors, while the use of aluminum and wood has been reduced due to a higher economic price.

Thermal insulation layer was introduced into envelope structure in the 1980s, following the adoption of the first standards on thermal protection of buildings. Expanded polystyrene (commercially known as ‘stropor’) and the rock wool are the most commonly used thermal insulation materials. To this day, nevertheless, most houses in Serbia are still not thermally insulated or are insulated to an insufficient extent.

3.1. Case Study House

Thermal-related characteristics of family houses from different regions of the Republic of Serbia are presented in detail in research publication Atlas of Family Housing in Serbia [25]. One of the basic types elaborated in Atlas—the town house—was chosen in this research
to test functionality and the effectiveness of proposed methodology for integrating the circularity principles into energy refurbishment plans.

Relevant U-values and annual heating energy consumption for selected two-storey family house located in historical urban core of Belgrade [25] (pp. 184–187) were calculated by using the software DesignBuilder version 5.03.007. Calculation results are presented in Table 2.

Table 2. Thermal envelope structure (according to [25]), U-values and annual heating energy consumption for selected house (original state).

| Envelope Elements | Layers (Outermost to Innermost) | U-Value (W/m²K) | Umax (W/m²K) [27] | QH,nd max (kWh/m²) [27,28] |
|-------------------|---------------------------------|----------------|------------------|---------------------------|
| External wall     | Cement plaster Solid brick Gypsum plaster | 1.195 | ≤ 0.4          |                           |
| Transparent part  | Wooden frames + clear glass     | 1.96 | ≤ 1.5          |                           |
| Ground floor      | Urea formaldehyde foam Cast concrete Floor screed Timber flooring | 0.250 | ≤ 0.4          |                           |
| Floor to unheated attic | Rammed earth Timber flooring Air gap Perlite plaster | 0.731 | ≤ 0.4          |                           |
| Roof unheated     | Clay tile (roofing) Air gap Roofing felt | 2.93 | ≤ 0.2          |                           |

Except for the ground floor, all other U-values calculated for the elements of existing thermal envelope are above the limit set by national regulations on energy efficiency of buildings [27,28], and the same refers to the calculated annual heating energy consumption. These findings justify the need for energy refurbishment of selected house.

3.2. Energy Refurbishment Scenarios

Five proposed scenarios for thermal upgrade of solid façade walls and three sub-scenarios for windows (Table 3) were modelled in the mentioned version of software DesignBuilder (Figure 1).

![Figure 1. Case study house modelled in DesignBuilder.](image-url)
Table 3. Scenarios of thermal upgrade of façade walls and the windows at selected house.

| Scenario | Main Features: Insulation Materials; Window Components |
|----------|--------------------------------------------------------|
| S.1      | Rock wool; Polyvinylchloride frames + insulation glass |
| S2.A     | Polyurethane; Aluminum frames + insulation glass       |
| S2.W     | Polyurethane; Wooden frames + insulation glass          |
| S3.A     | Reed boards; Aluminum frames + insulation glass         |
| S3.W     | Reed boards; Wooden frames + insulation glass           |
| S4.A     | Thermal plaster + green wall; Aluminum frames + insulation glass |
| S4.W     | Thermal plaster + green wall; Wooden frames + insulation glass |
| S5.A     | Thermal coating + thermal plaster; Aluminum frames + insulation glass |
| S5.W     | Thermal coating + thermal plaster; Wooden frames + insulation glass |

S1 scenario presents those façade thermal improvement measures that are nowadays most commonly used in Serbia, that is, rock wool insulation layer applied to the external side of the existing façade wall (7 cm thick in this case), PVC window frames with five chambers, and double-glazing panes with low-E coatings. Top plaster layer is with the same characteristics as in original state.

Scenario S2 foresees the application of an additional external, 7 cm thick thermal insulation layer of polyurethane cut from blocks with thermal bulk properties (conductivity 0.028 W/mK, specific heat 1,590.00 J/kgK, density 35 kg/m$^3$). Sub-variant S2.A features enhanced aluminum frames with thermal break and double low-E glazing, while S2.W refers to the wooden frames with the low-E double-glazing panes.

In the S3 scenario, 10 cm thick bio-based reed boards were applied as an additional external thermal insulation layer. The characteristics of the top plaster layer are the same as in existing state.

The characteristic of windows in sub-variants S3.A, S4.A and S5.A are the same as in S2.A, while sub-variants S3.W, S4.W and S5.W are equal to the described S2.W.

Option S4 features the combination of newly introduced external thermal plaster (4 cm) and 10 cm thick vegetation layer installed on 4 cm thick felt, while the air cavity of 10 cm has been excluded from thermal calculations.

Finally, S5 is an advanced scenario of applying the nano thermal coating from the inner [29] and the thermal plaster from external side of existing façade wall. Selected type of nano coating (conductivity 0.0016 W/mK) is available on Serbian market.

The U-values achieved by applying the scenarios described above, as well as the associated reduction in annual heating energy consumption are presented in Table 4. All proposed scenarios lead to the fulfillment of the requirements set in national regulations, in terms of maximum allowed U-values [27].

3.3. Multi-Criteria Assessment of Proposed Scenarios

By combining five different options for thermal insulation, and three options for windows, nine alternative solutions for thermal upgrade of façades of selected existing house were generated (Table 3).

Five types of defined assessment criteria: Economic Cost, Function, Circularity Features, Appearance, and Innovativeness were further worked out by introducing the corresponding indicators.

For criterion Economic Cost, the main indicator was the initial cost of a proposed solution, representing the sum of costs for material/components supply and their installation. Therefore, this criterion is expressed in Euros per square meter (€/m$^2$) of a proposed façade thermal upgrade solution.

The indicator for criterion Function refers to the calculated savings in annual heating energy consumption, achieved by applying proposed scenarios (Table 4), in comparison
with the existing state. Hence, criterion Function specifies the % of annual heating energy savings. Baseline to define indicators for criterion Circularity Features were the principles of circular economy shown in Table 1. Each proposed scenario and each circularity principle were assessed and assigned with points in range from 0.5–10 (1 point for each circularity principle, and 0.5 points for separate solutions for proposed thermal insulation materials and the window components). Both the windows and the wall insulation materials were treated as equally significant components because of their nearly equal contribution to the energy efficiency achievement.

Table 4. U-values and annual heating energy consumption in five scenarios of façade upgrade.

| Scenario | U-Value (W/m²K) | Q_{H,nd} (kWh) |
|----------|-----------------|----------------|
|          | Wall            | Glass/Frame    |                  |
| S1       | 0.338           | 1.267/1.430    | 12,086.29        |
| S2.A     | 0.305           | 1.267/3.471    | 11,962.55        |
| S2.W     | 1.267/1.335     | 11,713.82      |
| S3.A     | 0.339           | 1.267/3.471    | 12,191.14        |
| S3.W     | 1.267/1.335     | 11,948.72      |
| S4.A     | 0.399           | 1.267/3.471    | 12,521.00        |
| S4.W     | 1.267/1.335     | 12,286.25      |
| S5.A     | 0.401           | 1.267/3.471    | 14,010.62        |
| S5.W     | 1.267/1.335     | 13,785.66      |

For criteria Appearance and Innovativeness, a simplified Delphi method on the sample of 20 respondents-practicing architects or civil engineers-has been applied. Here, the respondents were given a possibility to assign to each individual thermal upgrade solutions from 1–10 points based on subjective visual impression, and from 1–10 points based on performance, availability on national market, expert opinion on working with proposed materials, and compliance with advanced circularity principles in national terms—potential for sharing and service provision.

Table 5 summarizes all indicators and criteria applied in assessment of alternative solutions for thermal upgrade of façade walls, and Table 6 presents obtained numerical values, i.e., statistically processed evaluation results for those criteria.

Table 5. Summary of criteria and their indicators applied in assessment of proposed façade upgrade solutions.

| Criteria by Type | Extremum | Indicators |
|------------------|----------|------------|
| Economic cost    | min      | Initial cost of proposed thermal envelope solution (in €/m²) |
| Function         | max      | Heating energy savings achieved by applying proposed solutions in comparison to the existing state (in %) |
| Circularity features | max      | Compliance with the principles of circularity (score 0.5–10, 1 point for each principle, i.e., 0.5 points for individual wall and window solutions) |
| Appearance       | max      | Visual impression of proposed solutions, expressed as average quantitative score obtained from respondents |
| Innovativeness   | max      | Average quantitative score obtained from respondents; assessment based on high performance, market availability, expert opinion, and compliance with advanced circularity principles |
3.4. Determination of Weighting Coefficients

Following determination of extremums (Table 5), the numerical values of criteria (Table 6), and before applying VIKOR method, it is necessary to define weighting coefficients for given criteria. To ensure a detailed analysis, three sets of weighting coefficients representing the preferences of decision makers have been introduced (Table 7).

**Table 7. Weighting coefficients.**

|       | Economic Cost | Function | Circularity | Appearance | Innovativeness |
|-------|---------------|----------|-------------|------------|----------------|
| WK1   | 0.35          | 0.35     | 0.20        | 0.10       | 0.10           |
| WK2   | 0.10          | 0.15     | 0.30        | 0.15       | 0.30           |
| WK3   | 0.20          | 0.20     | 0.20        | 0.20       | 0.20           |

In the first set of weighting coefficients (WK1), the decision maker gives the greatest importance to economic-financial aspects (criteria Economic cost and Function), followed by Circularity Features, and criteria Appearance and Innovativeness are considered the least important ($\omega_1 = \omega_2 = 0.35; \omega_3 = 0.20; \omega_4 = \omega_5 = 0.10$). In such order of significance, the decision maker indicates his main goal to achieve the greatest possible heating energy savings with as little financial investment as possible, i.e., to recover investment as soon as possible. This case is typical for situations where the decision maker’s budget is limited. The criteria that are given priority are directly opposed to each other (minimum investment–maximum return).

The second set of weighting coefficients (WK2) gives preference to Circularity Features and the Innovativeness. Less significance is given to the criteria Function and Appearance, while the Economic Cost is the least important criterion in this weighting set ($\omega_3 = \omega_5 = 0.30; \omega_2 = \omega_4 = 0.15; \omega_1 = 0.10$). Such a hierarchy directly supports circular economy and the economic growth, and at the same time, it enables non-conflict coexistence with the criteria Function and Appearance. On the other side, the order established by the WK2 directly confronts the criterion Economic Cost, as it stimulates investments in circularity (and energy efficiency) regardless of the amount of expenses.

In the third set of weighting coefficients (WK3), all criteria are equally significant to decision maker ($\omega_1 = \omega_2 = \omega_3 = \omega_4 = \omega_5 = 0.20$). In this case, criterion Economic Cost is confronted with all other criteria: minimal investment against maximal savings, maximal visual quality, maximum circularity features and maximal innovativeness.
4. Results

The application of the VIKOR method, according to the established methodology, criteria, indicators, and appropriate weighting coefficients results in ranking lists of alternative solutions. The use of three sets of weighting coefficients (Table 7) dictates the formation of three ranking lists on the basis of which the best offered alternative solution will be determined.

The method gives results according to the QR-minimax strategy (pessimistic results) and the QS-major benefit (expected results) (Table 8). Based on these results, the program calculates a compromise solution, which is the basis for ranking the offered alternative solutions (Table 9). The best solution has the lowest ranking value.

Table 8. Pessimistic and expected results with different weighting coefficients.

| Scenario | WK1   | WK2   | WK3   |
|----------|-------|-------|-------|
|          | QR    | QS    | QR    | QS    | QR    | QS    |
| S1       | 0.182 | 0.275 | 0.300 | 0.609 | 0.200 | 0.513 |
| S2.A     | 0.179 | 0.203 | 0.090 | 0.213 | 0.120 | 0.288 |
| S2.W     | 0.168 | 0.206 | 0.053 | 0.142 | 0.105 | 0.191 |
| S3.A     | 0.120 | 0.408 | 0.250 | 0.559 | 0.167 | 0.524 |
| S3.W     | 0.109 | 0.386 | 0.300 | 0.604 | 0.200 | 0.508 |
| S4.A     | 0.279 | 0.418 | 0.088 | 0.185 | 0.175 | 0.306 |
| S4.W     | 0.267 | 0.346 | 0.084 | 0.121 | 0.168 | 0.217 |
| S5.A     | 0.318 | 0.888 | 0.240 | 0.690 | 0.200 | 0.793 |
| S5.W     | 0.306 | 0.799 | 0.180 | 0.597 | 0.192 | 0.706 |

Table 9. Compromise results with different weighting coefficients, and ranking of solutions.

| Scenario | WK1   | WK2   | WK3   |
|----------|-------|-------|-------|
|          | Q     | Rank  | Q     | Rank  | Q     | Rank  |
| S1       | 0.275 | 5     | 0.915 | 9     | 0.720 | 7     |
| S2.A     | 0.203 | 4     | 0.157 | 4     | 0.159 | 2     |
| S2.W     | 0.112 | 1     | 0.022 | 1     | 0.00  | 1     |
| S3.A     | 0.198 | 3     | 0.781 | 6     | 0.591 | 5     |
| S3.W     | 0.158 | 2     | 0.910 | 8     | 0.716 | 6     |
| S4.A     | 0.510 | 7     | 0.124 | 3     | 0.409 | 4     |
| S4.W     | 0.424 | 6     | 0.050 | 2     | 0.290 | 3     |
| S5.A     | 0.888 | 9     | 0.903 | 7     | 1.000 | 9     |
| S5.W     | 0.799 | 8     | 0.707 | 5     | 0.882 | 8     |

According to the results shown in Table 9, the following can be concluded:

- For weighting coefficients WK1, the first-ranked compromise solution for the final decision is S2.W. In the set of offered alternative solutions, S2.W has an advantage of 4.7% when compared to the second-ranked alternative solution S3.W, and 8.7% over the third-ranked S3.A;
- For weighting coefficients WK2, the first-ranked compromise solution for the final decision is S2.W, with an advantage of 2.9% over the second-ranked alternative solution S4.W, and 10.3% over the third-ranked solution S4.A;
For weighting coefficients WK3, the first-ranked compromise solution for the final decision is S2.W, with sufficiently large advantage (15.9%) compared to the second-ranked solution S2.A.

To verify derived ranking results, the Spearman’s rank correlation coefficient was used as an additional assessment tool. Obtained values are shown in Table 10.

Table 10. Spearman’s rank correlation coefficients.

|     | WK1  | WK2  | WK3  |
|-----|------|------|------|
| WK1 | 1    | 0.128| 0.622|
| WK2 | 1    | 0.77 |      |
| WK3 | 1    |      | 1    |

Based on results of calculations presented in Table 10, it can be concluded that the obtained ranking order deviates from other weighting coefficients when the WK1 set is applied. The reason is that the Economic Cost criterion (minimum) deviates the most from other criteria (maximum), and the set WK1 prefers exactly that criterion the most. On the other hand, the correlation within the ranking order of solutions using weighting coefficients WK2 and WK3 displays a strong coherence. Based on ranking results and their verification by using the Spearman’s rank correlation coefficient, the logical choice for decision maker is the solution S2.W.

5. Discussion and Conclusions

The concept of circular economy in Serbia is at an early stage of development [12]. Although the number of indicators introduced to measure the circularity-related quality [30] is increasing internationally, construction materials and components available on the national market have not yet been subject to explicit requirements that strengthen the circularity schemes.

Through a series of established parameters, this research aimed to point out the possibilities of applying the elements of circular economy in a particular case from architecture, and thus contribute to better understanding of the concept. To that end, a preliminary analysis has led this study to establishing the fundamental list of circularity principles, among them, the biodegradability (recovery) is still insufficiently exploited in published literature [31].

Identified principles were subsequently applied to the specific case of existing house subjected to energy refurbishment. It has been found that the façade thermal upgrade can be carried out using those materials and components that correspond to often more than one circularity principle. To support the selection of optimal insulation materials and window components for façade thermal upgrades, the research has introduced the method of multi-criteria evaluation together with the corresponding criteria and indicators. Multi-criteria assessment is a well-known and widely-used method for evaluating different aspects of building envelopes e.g., [32–34], but its application in the context of optimization between energy refurbishment and multiple circularity features has not been found in examined body of literature [31].

Identified principles were subsequently applied to the specific case of existing house subjected to energy refurbishment. It has been found that the façade thermal upgrade can be carried out using those materials and components that correspond to often more than one circularity principle. To support the selection of optimal insulation materials and window components for façade thermal upgrades, the research has introduced the method of multi-criteria evaluation together with the corresponding criteria and indicators. Multi-criteria assessment is a well-known and widely-used method for evaluating different aspects of building envelopes e.g., [32–34], but its application in the context of optimization between energy refurbishment and multiple circularity features has not been found in examined body of literature. A particular advantage of responding positively to multiple circularity features reflects in a wider spectrum of possibilities for material treatment following its first utilization.

Using the selected VIKOR method, the multicriteria evaluation of five proposed scenarios to improve thermal characteristics of house façades was conducted. The scenarios were defined based on the type of thermal insulation material, namely rock wool, polyurethane, reed, vegetation, thermal plaster, and thermal nano coating. Belonging sub-scenarios, on the other hand, referred to the type of material for window frames: PVC, aluminum, or natural wood. Furthermore, the assessment of proposed alternative solutions was performed according to three determined sets of weighting coefficients.
Based on conducted analyses, and the results obtained from them, it was concluded that the S2.W solution—proposing the use of polyurethane thermal insulation and the wooden window frames with double low-E glass—represents the optimal choice for thermal upgrade of façades of existing family houses in Serbia, taking into consideration the initial cost, achievable heating energy savings, compliance with several circularity principles, good visual appearance, high performance, availability on national market, etc.

Although the final proposal to improve thermal characteristics of façades of family houses concurrently contributes to encouraging the circularity and achieving the energy efficiency, this solution could be subjected to additional analyses before entering practical use. Namely, the resulting proposal S2.W shows that there is a gap between circularity and environmental sustainability [5,35,36] that could lead to incomplete decision-making with ecological consequences. As previously noted by Haupt and Hellweg, the results of present research have confirmed that circularity is not necessarily equivalent to environmental sustainability [37]. Standard, non-bio-based polyurethane, as seen in the research, can be accepted in terms of several fundamental circularity principles, but this material also has several notable ecologically negative points concerning raw materials [38] and production [39], especially when compared to other materials proposed in this research, such as reed or living vegetation. For that reason, it is necessary to include into future multi-criteria analyses the life cycle-based environmental quality [37,40,41] as one of the principal assessment criteria, and overcome the revealed weakness of methodology proposed in this research, accordingly. In addition, bearing in mind that many of the existing houses in cities and towns are located in central zones, the energy refurbishment process should be carried out not only in accordance with the principles of circularity and environmental sustainability, but also the principles of heritage protection [42].

**Author Contributions:** Conceptualization, S.K. and M.M.; methodology, L.M., M.M. and S.K.; software, M.M. and L.M.; validation, L.M., M.M. and S.K.; analyses L.M., M.M. and S.K.; investigation, S.K., L.M. and M.M; resources, S.K., L.M. and M.M.; writing—original draft preparation, S.K., L.M and M.M.; writing—review and editing, S.K.; visualization, L.M., S.K. and M.M.; supervision, S.K., L.M. and M.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to efficiency in research presentation.

**Acknowledgments:** The authors express their gratitude to Reviewers, Special Issue Guest Editors and the Editors of the journal Sustainability for timeliness, good collaboration and helpful comments.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Lewandowski, M. Designing the business models for circular economy—Towards the conceptual framework. *Sustainability* **2016**, *8*, 43. [CrossRef]

2. Kosanović, S. Istraživanje Mogućnosti za Promenu Ekoloških Uticaja Zgrada na Okruženje. Master’s Thesis, Univerzitet u Beogradu, Arhitektonski fakultet, Belgrade, Serbia, 2007.

3. Klein, M.; Osterhage, T.; Muller, D.; Kosanović, S.; Hildebrand, L. Building certification systems and processes. In *Sustainable and Resilient Building Design: Approaches, Methods and Tools*; Kosanović, S., Klein, T., Konstantinou, T., Radivojević, A., Hildebrand, L., Eds.; TU Delft Open: Delft, The Netherlands, 2018; pp. 83–98.

4. Ellen MacArthur Foundation. Concept: What is a Circular Economy? A Framework for an Economy That is Restorative and Regenerative by Design. Available online: https://www.ellennmacarthurfoundation.org/circular-economy/concept (accessed on 31 March 2021).

5. Korhonen, J.; Honkasalo, A.; Seppälä, J. Circular economy: The concept and its limitations. *Ecol. Econ.* **2018**, *143*, 37–46. [CrossRef]

6. Hildebrand, L.; Konstantinou, T.; Kosanović, S.; Klein, T.; Knaack, U. Origin and development of environmental design. In *Sustainable and Resilient Building Design: Approaches, Methods and Tools*; Kosanović, S., Klein, T., Konstantinou, T., Radivojević, A., Hildebrand, L., Eds.; TU Delft Open: Delft, The Netherlands, 2018; pp. 17–36.
Sustainability 2021, 13, 5463

7. Kosanović, S. Model for Ocenu Ekološke Ispravnosti Kuća za Individualno Stanovanje na Području Beograda. Ph.D. Thesis, Univerzitet u Beogradu, Arhitektonski fakultet, Belgrade, Serbia, 2012.

8. Zairul, M.N.; Geraedts, R. New business model of flexible housing and circular economy. In Proceedings of the Future of Open Building Conference, ETH-Zürich, Switzerland, 9–11 September 2015; ETH-Zürich: Zürich, Switzerland, 2015. [CrossRef]

9. Allam, Z.; Jones, D.S. Towards a circular economy: A case study of waste conversion into housing units in Cotonou, Benin. Urban Sci. 2018, 2, 118. [CrossRef]

10. Galle, W.; Debacter, W.; De Weerdt, Y.; De Temmerman, N. Housing in the circular economy; lessons from value network mapping as a transition experimentation tool. In Proceedings of the International Sustainability Transitions Conference 2019, Ottawa, ON, Canada, 23–26 June 2019; Carleton University: Ottawa, ON, Canada, 2019.

11. Pravilnik o Blizim Uslovima, Kriterijumima i Postupku za Dobijanje Prava na Korišćenje Ekološkog znaka, Elementima, Izgledu i Načinu Upotrebe Ekološkog Znaka za Proizvode i Usluge. 2016. Available online: https://www.paragraf.rs/propisi/pravilnik_o_blizim_uslovima_kriterijumima_i_postupku_za_dobijanje_prava_na_korisnecenjeEkološkog_znaka_elementima_izgledu_iNačinu_upotrebeEkološkog_znaka_za_proizvode_i_usluge.html (accessed on 5 May 2021).

12. Ministarstvo Zaštite ZIVOTNE SREDINe Republike Srbije. Mapa puta za Cirkularnu ekonomiju u Srbiji. Available online: https://www.ekologija.gov.rs/sites/default/files/2021-01/mapa-puta-za-cirkularnu-ekonomiju-u-srbiji.pdf (accessed on 30 March 2021).

13. Ministarstvo Rudarstva i Energetike Republike Srbije. Mihajlovićeva: Nova Uprava za Podršku Građanima da Povećaju Energetsku Efikasnost u svojim Domacinstvima. Available online: https://www.mre.gov.rs/aktuelnosti/saopstenja/mihajloveceva-nova-uprava-za-podrsku-gradjanima-da-povecaju-energetsku-efikasnost-u-svojim-domacinstvima (accessed on 30 March 2021).

14. Cooper, S.J.G.; Giesekam, J.; Hammond, G.P.; Norman, J.B.; Owen, A.; Rogers, J.G.; Scott, K. Thermodynamic insights and assessment of the ‘circular economy’. J. Clean. Prod. 2017, 162, 1356–1367. [CrossRef]

15. Kansters, J. Circular building design: An analysis of barriers and drivers for a circular building sector. Buildings 2020, 10, 77. [CrossRef]

16. Xu, L.; Yang, J. A.E. Marković, L.; Cvetković, M.; Milić Marković, L. Multi-criteria decision-making when choosing variant solution of highway route at the level of preliminary design. Facta Universitatis Ser. Archit. Civil Eng. 2013, 11, 71–87. Available online: http://www.doiserbia.nb.rs/img/doi/0354-4605/2013/0354-46051301071M.pdf (accessed on 5 April 2021). [CrossRef]

17. Department for Communities and Local Government. Multi-criteria Analysis: A Manual; Communities and Local Government Publications: London, UK, 2009. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/191506/Mult-crisis_analysis_a_manual.pdf (accessed on 30 March 2021).

18. Opricovic, S.; Tzeng, G.-H. The compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. Eur. J. Oper. Res. 2004, 156, 445–455. [CrossRef]

19. Science Watch. April 2009—Emerging Research Fronts: Serafim Opricovic & Gwo-Hshiung Tzeng. Available online: http://archive.sciencewatch.com/dr/erf/2009/09aprerf/09aprerfOpriET/ (accessed on 16 March 2021).

20. Opricovic, S.; Tzeng, G.-H. Extended VIKOR method in comparison with outranking methods. Eur. J. Oper. Res. 2007, 178, 514–529. [CrossRef]

21. Pravilnik o energetskoj efikasnosti zgrada. Sl. Glas. RS 2011, 61, 2011.

22. Pravilnik o Uslovima, Sadržini i Načinu Izdavanja Sertifikata o Energetskim Svojstvima Zgrada. 2018. Available online: https://www.paragraf.rs/propisi/pravilnik_o_uslovima_sadrzini_i_nacinu_izdavanja_sertifikata_o_energetskim_svojstvima_zgrada.html (accessed on 5 May 2021).

23. Ahmad, R.; Osama, F.; Wael, M. Energy performance analysis of integrating building envelopes with nanomaterials. Int. J. Sustain. Built Environ. 2013, 2, 209–223. [CrossRef]

24. Lehman, A.; O’Rourke, N.; Hatcher, L.; Stepanski, E.J. JMP for Basic Univariate and Multivariate Statistics: A Step-by-Step Guide; SAS Press: Cary, NC, USA, 2005.

25. Jovanović Popović, M.; Ignjatović, D.; Đorđević, M.; Božović, M.; Čuković Ignjatović, N.; Nedči, M. Atlas porodičnih kuća Srbije; Arhitektonski fakultet Univerziteta u Beogradu i GIZ—Deutsche Gesellschaft fur internationale Zusammenarbeit: Belgrade, Srbija, 2012.

26. Kosanović, S.; Folić, B.; Kovačević, S.; Nikolić, I.; Folić, L. A study on the sustainability of the traditional Sirinić houses in the Sar Mountain Region, the South-Western Balkans. Sustainability 2019, 11, 4711. [CrossRef]

27. Šaljuković, Z.; Jovanović Popović, M.; Ignjatović, D.; Đorđević, M.; Božović, M.; Čuković Ignjatović, N.; Nedči, M. Atlas porodičnih kuća Srbije; Arhitektonski fakultet Univerziteta u Beogradu i GIZ—Deutsche Gesellschaft fur internationale Zusammenarbeit: Belgrade, Srbija, 2012.

28. Ahmad, R.; Osama, F.; Wael, M. Energy performance analysis of integrating building envelopes with nanomaterials. Int. J. Sustain. Built Environ. 2013, 2, 209–223. [CrossRef]

29. Ahmad, R.; Osama, F.; Wael, M. Energy performance analysis of integrating building envelopes with nanomaterials. Int. J. Sustain. Built Environ. 2013, 2, 209–223. [CrossRef]
33. Nadoushani, Z.S.M.; Akbarnezhad, A.; Jornet, J.F.; Xiao, J. Multi-criteria selection of façade systems based on sustainability criteria. *Build. Environ.* **2017**, *121*, 67–78. [CrossRef]

34. Seddiki, M.; Anouche, K.; Bennadj, A.; Boateng, P. A multi-criteria group decision-making method for the thermal renovation of masonry buildings: The case of Algeria. *Energ Build.* **2016**, *129*, 471–483. [CrossRef]

35. Lonca, G.; Muggé, R.; Imbeault-Tétreault, H.; Bernard, S.; Margni, M. Does material circularity rhyme with environmental efficiency? Case studies on used tires. *J. Clean. Prod.* **2018**, *183*, 424–435. [CrossRef]

36. Niero, M.; Kalbar, P.P. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. *Resour. Conserv. Recy.* **2019**, *140*, 305–312. [CrossRef]

37. Haupt, M.; Hellweg, S. Measuring the environmental sustainability of a circular economy. *Environ. Sustain. Indic.* **2019**, *1–2*, 100005. [CrossRef]

38. Pargana, N.; Pinheiro, M.D.; Silvestre, J.D.; de Brito, J. Comparative environmental life cycle assessment of thermal insulation materials of buildings. *Energy Build.* **2014**, *82*, 466–481. [CrossRef]

39. Fridrihsone, A.; Romagnoli, F.; Kirsanovs, V.; Cabulis, U. Life Cycle Assessment of vegetable oil based polyols for polyurethane production. *J. Clean. Prod.* **2020**, *266*, 121403. [CrossRef]

40. Walker, S.; Coleman, N.; Hodgson, P.; Collins, N.; Brimacombe, L. Evaluating the environmental dimension of material efficiency strategies relating to the circular economy. *Sustainability* **2018**, *10*, 666. [CrossRef]

41. Walzberg, J.; Lonca, G.; Hanes, R.J.; Eberle, A.L.; Carpenter, A.; Heath, G.A. Do we need a new sustainability assessment method for the circular economy? A critical literature review. *Front. Sustain.* **2021**, *1*, 620047. [CrossRef]

42. Foster, G. Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Resour. Conserv. Recy.* **2020**, *152*, 104507. [CrossRef]