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AHP-Based Model for Energy-Sustainable Renovation of Building Envelopes: A Case Study

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Abstract: The EU's low carbon transition relies on the building sector as one of its main pillars, given that around 85% of the 160 million buildings within the EU are thermally inefficient. The energy-sustainable renovation of building envelopes calls for a comprehensive approach from initial design phases to construction, while balancing a series of factors, e.g., function and aesthetics, energy savings and environmental concerns, as well as cost-effectiveness. This article develops a model for the energy-sustainable renovation of building envelopes based on a multi-criteria analysis method—the AHP method. The model facilitates problem solving and development of alternative designs. The AHP method is used for evaluating and narrowing down design variants considering the given building conditions and the adopted set of criteria. The developed model is also applied in a real case study—the envelope energy renovation of a typical residential building built after the 1950s in many suburbs of Belgrade, Serbia. The model developed in the paper may be used by professionals to facilitate and make more efficient the design process of the energy-sustainable renovation of buildings and can inspire further studies on this topic, which has grown in urgency amid the current global energy crisis.

Keywords: analytical hierarchy process (AHP); building envelope; energy-sustainable renovation (ESR); multi-criteria decision making (MCDM); residential building; solar thermal collectors (STCs); case study

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1. Introduction

The transition towards a low-carbon future in the EU largely depends on the building sector [1–3]. Until the 1970s buildings were designed without optimized energy performance in terms of energy demands and consumption, and newly built energy-efficient buildings now make up a small share of the existing building stock. According to some estimates, at least 75% of EU buildings need to be made more energy efficient [4]. Energy renovations of the building envelope and its technical systems aimed at energy efficiency improvements, together with renewable energy technology installations, have been recognized as a key vehicle for achieving the EU energy efficiency target for 2030 and the transition towards climate-neutral Europe by 2050 [3].

An EU-wide definition of energy renovation does not exist. It can be described in terms of a set of intervention measures undertaken for the energy improvement of the building envelope, building technical systems, and renewable heat and electricity generation systems, and incorporation of 'smart' technologies. While it is widely acknowledged that an energy renovation should lead to certain energy savings after the intervention work is carried out, the link between the 'depth' of building energy renovation and the resulting energy savings is not clear [3]. The most commonly applied measures refer to energy improvement of the building envelope. This includes different technologies and measures applied to the transparent and non-transparent parts of the building envelope, i.e., the use of different thermal insulation systems of external walls, lofts, and roofs; installation of solar shading systems and ventilated facades; over-cladding and re-cladding using resource-efficient building materials; replacement of windows and doors; and introduction of natural ventilation and passive solar heating/cooling techniques.

Furthermore, the share of renewable energy sources (RESs) in gross final energy consumption (GFEC) across the EU has more than doubled in recent years, from 9.6% in 2004 to 21.8% in 2021 [5]. With RESs accounting for more than half of the energy in its GFEC, Sweden (62.6%) had by far the highest share among the EU Member States in 2021, ahead of Finland (43.1%) and Latvia (42.1%). These data reflect the fact that 'these technologies have become more accessible and citizens have become more empowered' [6]. In addition, the Clean Energy for all Europeans package [7] and the recast Renewable Energy Directive [8] make it easier for citizens to form energy communities, but also to produce, store, and sell their own renewable energy.

In the Republic of Serbia, energy efficiency is a high-priority matter. In the area of final energy consumption and energy sources in buildings, energy efficiency is regulated by the Law on Energy Efficiency and Rational Use of energy [9], the Law on Construction and Planning [10], the Rulebook on energy efficiency of buildings [11], and the Rulebook on the conditions, content, and manner of issuance of certificates of energy performance of buildings [12]. These regulations transpose the requirements of the EU Energy Performance of Buildings Directive (EPBD 2010/31/EU) [13], and the Energy Efficiency Directive (EED 2012/27/EU) [14–16] regarding energy efficiency of final consumption and energy services. The Directive amending the Energy Performance of Buildings Directive [15] introduced new elements and sent a strong political signal regarding the EU's commitment to modernize the buildings sector in light of technological improvements and to increase building renovations. According to the data collected by the Statistical Office of the Republic of Serbia, approximately 55% of a total of 583,908 existing housing units in Belgrade were built in the period before the 1970s [16]. This figure reveals that Belgrade's building stock has a significant number of buildings whose energy and environmental performance has to be improved. Therefore, significant energy efficiency can be achieved by an appropriate choice of energy renovation technologies.

The political aspect of feed-in tariff values for energy from renewable sources in Serbia is in line with the Directive (2009/28/EC) [17] and the Energy Community Ministerial Council Decision (D/2012/04/MC-EnC) [18], according to which Serbia (as a signatory of the Agreement of Energy Community) was obliged to achieve a very demanding and binding goal of a 27% share of RESs in GFEC in 2020. However, the results show that the share of RES in GFEC in 2019 was 21.44%, instead of the planned 25.6% [19]. In the previous period, the Republic of Serbia implemented the reform and drafted a large number of by-laws in order to align its policy in the process of European integration with the latest EU regulations in the field of RESs and their ambitious goals. The long-term goal requires global greenhouse gas emissions to be reduced by at least 80% below the 1990 levels by 2050 [20,21], while developed countries should reduce their emissions to 80–95% compared to 1990 levels within the same period [22]. Countries in transition, such as Serbia, and developing countries, need to continue to follow this guideline when it comes to the construction sector; it is necessary to introduce appropriate low-carbon technologies to build new energy-efficient buildings and to renovate the existing ones.

This paper proposes a model (framework) for energy-sustainable renovation (ESR) of residential buildings' envelopes based on a multi-criteria analysis method—the AHP method. The model provides clear and systematic guidelines from the conceptual phase of designing alternatives to the phase of deciding on the 'best' one with respect to the adopted set of criteria and the given constraints related to the building's characteristics and context. Through the presented real problem and using real data—the ESR of the envelope of a residential building in the suburb of 'Konjarnik', in Belgrade, Serbia—each step of the proposed model is systematically explained and the applicability of the model is validated.

An iterative procedure was adopted for the process of designing alternative solutions, keeping in mind the complexity of the problem and the need to strike a balance between mutually competing requirements in terms of function, energy performance, aesthetics, cost-effectiveness, and environmental concerns. The established procedure is presented and discussed in detail in Section 3, while in Section 4, the proposed model is applied to solving a real problem—the ESR of the envelope of a residential building in the suburb of 'Konjarnik', in Belgrade, Serbia, dating from the period after the Second World War. Each step of the proposed model is systematically presented and explained. The concluding remarks about the proposed methodology and its applicability are given in Section 5.

2. Literature Review

Around 75% of the total building stock in Europe comprises residential building, of which 36% are multi-apartment housing blocks, and more than half (57%) were built in the period before 1970 [23]. As they typically rely on low-cost technologies, most of these multi-family housing blocks are characterized by poor energy performance [24]. It is estimated that approximately 85% of the 160 million buildings within the European Union (EU) are energy-inefficient [25]. New construction accounts for only 1% of the annual addition to the total gross floor area in the EU [23], and in most industrialized countries by 2050 new buildings will only contribute 10%–20% to additional energy consumption, whereas more than 80% will continue to be consumed by the existing building stock [26]. Therefore, renovation is considered to be the primary factor in achieving the EU sustainability goals of becoming climate neutral by 2050 [27].

A number of studies have attempted to relate the 'depth' of renovation to relative energy savings. According to the European Building Performance Institute (BPIE), minor renovations account for 0–30% of the final energy savings, moderate renovations for 30–60%, and 'deep' renovations for 60–90%, while renovations of near-zero energy buildings (NZEBs) account for savings of more than 90% [28]. Conducting a cross-regional analysis, the authors in the study [29] concluded that 'deep' renovations can be associated with improvements of at least 75% and post-renovation primary energy consumption of less than 60 kWh/m^2 per year. This study focused mainly on the end uses of heating, cooling, ventilation, and hot water. Furthermore, an extensive body of studies assesses the energy consumption for space heating and domestic hot water, either in residential or public building stock, considering available technologies (heating and electric power systems), combined with renewable energy supply [30]. The analysis shows that significant progress is needed in order to increase the annual rates of building energy renovation (by 3% instead of the expected 2%) and that the NZEB principle needs to be respected in order to achieve the highest level of energy efficiency and meet the national and EU goals by 2050 [27].

2.1. Application of MCDM Methods in Sustainable Building Design and Construction

Recently, the MCDM process has become increasingly prominent in the field of construction sustainability, both in practice and in the academic community [31,32]. MCDM represents one of the most important fields of operations research dealing with problems that involve multiple and conflicting objectives [33]. MCDM is both an approach and a set of techniques, with the aim of providing an overall ordering of options, from the most preferred to the least preferred option [33,34]. MCDM approaches provide a systematic procedure to help decision makers choose the most desirable and satisfactory alternative in an uncertain situation [35]. From a technical-scientific point of view, decision-making support needs to justify its choices clearly and consistently, especially for addressing issues in connection with sustainability [36].

Furthermore, these methods are able to handle both quantitative and qualitative criteria and to manage tension between conflicting criteria and stakeholders' interests [37,38]. The use of MCDM and the method of multi-criteria decision analysis (MCDA) allows the problem to be considered at two different levels: at the managerial level, objectives are defined and the final optimal alternative is selected, while at the engineering level, alternatives are designed, a multi-criteria assessment of alternatives is performed, and the consequences of the choice are analyzed [39]. These elements have contributed to the increased use of MCDM and MCDA methods in building assessment procedures, providing a framework for evaluation and selection of sustainable building technology options in recent years.

Application of MCDM in ESR of Building Envelopes

The method proposed in [40] for optimizing the building envelope and technical equipment, the Weighted Sum Method, has been used to achieve a reduction in global investment cost, primary energy index, and carbon dioxide emission in relation to the basic scenario. Similarly, in [41], by using a genetic algorithm, NSGA-II, the authors analyzed the relationship between the initial characteristics of residential buildings and the optimal retrofit solutions in terms of either maximum economic performance or energy consumption reduction in NZEBs for the lowest achievable thermal discomfort. Giurca et al. in [42] developed a method for selecting technical solutions for the rehabilitation and thermal and energy modernization of buildings, using the TOPSIS method. In addition, by deeply investigating MCDM design methodologies and processes in the building renovation field, Kamari et al. in [43,44] introduced three sustainable retrofitting frameworks based on (1) application of MCDM including either multiple-attribute decision making (MADM) methods, (2) multiple-objective decision making (MODM), and (3) Holistic Multimethodology for Sustainable Building Renovation (HMSR), to help stakeholders in the renovation process make transparent decisions in a rational order.

Unlike previous studies, Dražić and Laban [45] proposed an evaluation and decision-making methodology for the selection of a specific building element—the most suitable type of window—which, in addition to economic-financial, technical, technological, and environmental assessments of considered window types, includes a decision flow algorithm and an optimization method. Similarly, by using multi-criteria analysis, a decision procedure for the most resilient design of a residential wall system was considered in [46] while maintaining the required thermal comfort under global warming and even during an extreme climate event.

An overview of the most recent studies regarding the use of MCDM methods in ESR of building envelopes, published in 2020 or later, is given in Table 1. It can be noticed that almost all different methods are applied, across a variety of locations and building types selected for the case studies. According to the authors' knowledge, the latest example of use of the AHP method was on a cultural heritage building in Italy, where it was used to evaluate the restoration score and to create priorities among different alternative designs of the thermal envelope [47]. In addition, in order to discover opportunities for local clean solar energy production and utilization, by integration of solar thermal collectors (STCs) and PVs into the building envelope, including the facade and the roof, the renewable sources were analyzed using MCDM methods [48,49].

Table 1. Review of recent studies related to MCDM methods in ESR of building envelopes.

Year	Authors/Ref.	Approach/ Methods	Decision Area	Study Focus	Country/ Case Study
2023	Daniel and Ghiaus [50]	ELECTRE Tri	Identification/ selection	Proposal of renovation scenarios by combining individual actions that are mutually compatible to help choosing a retrofit program for collective residential building	France collective residential assembly composed of three buildings
2022	Prabatha et al. [51]	Min-Max method (fuzzy number ranking mechanism)	Evaluation/ assessment	Novel Energy Performance Contracts approach for residential building renovation projects allowing selection of contract parameters to promote energy retrofits to the rental building sector	Canada medium single-family detached house
2022	Ongpeng et al. [52]	Systematic hybrid decision framework AHP—VIKOR	Evaluation/ selection	Evaluation of energy retrofit strategies and identification of a compromise retrofit scenario considering all stakeholders involved	Philippines University of the Philippines—National Engineering Center
2022	Salvadó et al. [53]	Decision Support System (DSS)—algorithm	Evaluation/ assessment	Decision-support system for designers to choose a solution/technology, while considering conflicting criteria, and uncertainty, within a NZEB refurbishment process	/
2022	Romani et al. [54]	Comparison of multi-criteria analysis: Weighted Sum, Min-Max and Pareto concept	Assessment	Metamodeling and multi-criteria analysis for sustainable and passive residential building refurbishment by integrating different criteria throughout the building life cycle stages	France housing stock
2022	Sarmas et al. [55]	TOPSIS	Evaluation/ assessment	Solid methodological framework supporting the financing procedure of energy efficiency investments and identifying improved grant financing plans in terms of budget and energy saving	Latvia multiple buildings
2021	Egiluz et al. [56]	MIVES—(Integrated Value Model for Sustainability Assessment)	Selection	Selection of the most sustainable options of energetic retrofitting employing various facades solutions and materials by proposed decision-making methodology	Spain residential building
2020	Ruggeri et al. [47]	Score-driven decision support system (integration of different appraisal techniques—Multi-Attribute Analysis, Life Cycle Costing and AHP)	Evaluation/ selection	Management of energy retrofit interventions specifically applied to cultural heritage and historic buildings including safeguard and conservation aspects in the selection procedure	Italy cultural heritage building
2020	Starynina and Ustinovichius [57]	Synthesis of multiple-attribute decisions—SyMAD-3 (integration COPRAS-TOPSIS-SAW)	Evaluation/ assessment	Sustainable building modernization model using knowledge-based decision-making methods for old public building reconstruction, intending to achieve the best level of energy use	Lithuania Administrative building—Switching Control Centre
2022	Jahangiri et al. [48]	SWARA/ Comparison of multi-criteria analysis: EDAS, ARAS, WASPAS, TOPSIS	Evaluation/ selection	Climatic design framework examining degree of BIPV adoption to different weather conditions and finding the optimal configuration for placing solar cells on the building facade	Iran

Some other studies [58] discussed the application of MCDA methods in selecting energy supply systems, such as combined cooling, heating, and power (CCHP) systems together with renewable energy systems, from the technological, economic, and sustainability aspects. In addition, considering a large number of different criteria relevant for energy systems (i.e., (a) technical: energy efficiency, primary energy ratio, safety, reliability; (b) economic: investment cost, operation and maintenance cost, fuel cost, electric cost, net present value, payback period, service life; (c) environmental: emission of different gases, non-methane volatile organic compounds, land use, noise; and (d) social: social acceptability and social benefits), the authors [58] concluded that fewer criteria are more beneficial for sustainable energy decision making and proposed the methods for selecting the 'major' criteria.

2.2. Application of Hybrid MCDM Methods in Sustainable Building Design and Construction

Although the above-listed approaches provide an insight mainly into individual methods, an increasing use of hybrid tools, i.e., integration of different methods, can be observed recently, owing to their complementarity in fulfilling different tasks in complex design processes. The outcome of the integrated approach helps in prioritizing challenges and also in exposing the interrelationships among the challenges [59]. For example, Pinto et al. [60] describe the use of a hybrid method that integrates AHP and EVAMIX multi-criteria approaches to evaluate design alternatives with a view to improving a building's performance while preserving heritage identity. In another study [59], an integrated multi-criteria decision making (MCDM) technique comprising the Best–Worst Method (BWM) and Decision-Making Trial and Evaluation of Laboratory (DEMATEL) is used to evaluate the challenges to LCA. BWM is used to prioritize the challenges to LCA, indicating problems with the quality of data, lack of inventory data, difficulty in comparison, absence of a dedicated LCA method, and scale-up issues as the top five critical challenges to LCA adoption. By comparison, DEMATEL is used to reveal interrelationships among the challenges, according to which 7 challenges come under the cause category and the remaining 13 challenges come under the effect category.

Considering material selection as a typical multiple-criteria decision making (MCDM) problem, and decision progression with the intention of decreasing the number of possible material alternatives to the final choices, several studies have been conducted integrating different (MCDM) methods. A study [61] was aimed at developing the Combinative Distance-based Assessment (CODAS) method with target-valued attributes to achieve practical and functional applications, particularly in engineering design problems. Consequently, the Step-Wise Weight Assessment Ratio Analysis (SWARA) method has been combined with the proposed multi-attribute decision making (MADM) approach, as one of the extensions of MCDM techniques, to calculate the weights of the criteria. Along with the proposition of a novel and hybrid SWARA-CODAS TB approach, this study has also tackled a material selection problem in dam construction. Furthermore, Zolfani and Chatterjee [62] compare the results of variability between the criteria priorities for Step-Wise Weight Assessment Ratio Analysis (SWARA) and the Best–Worst Method (BWM) for weight derivation and make suggestions about the conditions of using these two methods for furnishing material selection problems in sustainable interior design.

Based on the literature review, it can be concluded that no studies provide a framework with clear guidelines about how to carry out an energy-sustainable renovation process of the building envelope with installation of solar collectors. This paper tries to fill the gap by proposing a model (framework) based on one of the widely used MCDM methods, the AHP method.

3. Materials and Methods

The methodology in this study may be divided into three phases: (1) literature review related to energy-sustainable renovation (ESR) of residential (multi-apartment) buildings and analysis of the AHP methodology and its application in the field of building renovation;

(2) development of a model for energy improvement of the building envelope based on the hierarchical multi-criteria analysis method—AHP method; and (3) application of the developed model to solve a real-life problem and to verify its validity.

3.1. Literature Review of ESR of a Residential Building and Analysis of AHP Methodology

This phase was conducted to answer the following three key questions: 'What are the building factors/parameters that must be taken into account to properly assess the existing building condition and determine adequate building energy improvement goals?'; 'What are the appropriate sustainable measures and technologies that could be applied to achieve building energy improvements goals'?; and 'What methods/tools can be used to support decision-making during building ESR process'?

To answer these questions, a detailed literature review was conducted in order to develop a suitable model for the energy renovation of the building envelope. Some relevant studies have already been discussed in Section 2, and the others are presented below in sub-Section 3.1.1 while describing and explaining the structure and modules of the proposed model. The selected case study represents a real problem that may also serve as a role model for solving the energy renovation problem of other similar buildings. All the data required for the calculation of the building's energy consumption for heating of premises, water heating, air conditioning, thermal characteristics, and prices of the energy insulation materials, together with the characteristics and prices of the solar water-heating system and transport and installation prices, are all real data taken from relevant sources.

3.1.1. Application of the AHP Method in Building Design

In building design, AHP is used as a tool to evaluate the relative importance of the criteria, sub-criteria, and groups of indicators established by the researchers and/or interested parties for assessing the building sustainability. This method can be applied both to the simplified processes in the early design phase and to the more complex ones, e.g., renovation of existing buildings [63–65] and 'intelligent' building systems as well [66]. Specifically, the extent to which AHP is effective for building a tailored weighting system for assessing building sustainability has been demonstrated by Wong and Li [66], Alkubaisi and Alnsour [67], Zheng, Jing, Huang, Zhang and Gao [68], and Donnarumma and Pierfrancesco [69], among others.

For modeling various problems in the field of building renovation, MCDMs have been often used and their application in various areas has increased significantly in recent years, especially with the design of new methods such as VIKOR, SWARA, BWM, OPA, among others, and the improvement of old ones [70], as well as the fuzzification of the traditional methods (e.g., fuzzy AHP, fuzzy ANP, fuzzy WSM, fuzzy TOPSIS, fuzzy ELECTRE, fuzzy PROMETHEE, and fuzzy COPRAS), including also the recent ones (fuzzy VIKOR, fuzzy SWARA, fuzzy BWM, etc.), to take into account the uncertainties inherent in real problems. According to Ab Taha and Daim [34], MCDM methods are flexible tools encompassing a wide range of variables and different ways of assessment, greatly facilitating problem mapping.

3.1.2. Characteristics of AHP for Its Applicability in Practice

The reasons for selecting the AHP method for solving the MCDM problem in the considered area (ESR of building envelope) were as follows: (1) The methodology has the capacity to break down a complex problem (such as the energy-sustainable building renovation problem) into simpler parts and solve them successively, allowing for a simple and clear calculation procedure. (2) It enables the participation of a group of experts and/or decision makers, which is usually required to solve energy-sustainable renovation problems of residential buildings in real life. Specifically, apart from the energy aspect, it is often necessary to evaluate alternative solutions in relation to aesthetic, functional, technical, economic, and ecological aspects, so the participation of a group of experts with different specialties can contribute to a better evaluation of the design alternatives.

(3) In order to assess the importance of the criteria (that directly affect the choice of the 'best' alternative) we commonly have in practice the case of multiple decision makers in the decision process (i.e., group of investors, management team of a company, group of tenants, etc.) and the AHP method supports their participation. (4) The possibility of checking the 'stability' of the leading alternatives by conducting 'Sensitivity analyses' is also an important feature of this method. It gives decision makers insight into the 'sensitivity' of the current ranking of alternatives (i.e., what is the smallest change in the weighting of the current criteria that can change the existing ranking), and thus gives a more accurate and broader perspective of the actual benefits of the 'best' alternatives. (5) The capacity to incorporate both qualitative and quantitative criteria that might have different units and scales without the need to transform them into the same scale (unit) contributes to the simplicity of use. (6) Finally, the support and availability of (free) computer programs for the application of this methodology (which also include the 'Sensitivity analysis' part) is another important feature that ensures its effective and wide application in the field of energy-sustainable renovation of the building envelope.

Its limitations are discussed in Section 5 while a concise comparison of the AHP characteristics with recent MCDMs, such as VIKOR (VlseKriterijumska Optimizcija I Kaompromisno Resenje in Serbian), SWARA (Step-Wise Weight Assessment Ratio Analysis), BWM (Best–Worst Method), and OPA (Ordinal Priority Approach), is given in Table 2 based on the study presented in [71].

Table 2. Comparison of MCDM methods: AHP, VIKOR, SWARA, BWM, and OPA based on a previous study [71].

No.	Characteristics of the Method	AHP (1972)	VIKOR (1998)	SWARA (2010)	BWM (2015)	OPA (2019)
1	Use of pairwise comparisons	Yes	No	No	Yes	No
2	Definition of decision matrix	Yes	Yes	Yes	Yes	No
3	Necessity to convert qualitative attributes into quantitative (numbers)	Yes	Yes	Yes	Yes	No
4	Need for normalization	No	Yes	No	No	No
5	Usage of an averaging method to aggregate expert opinions	Yes	Yes	Yes	No	No
6	Each alternative must be evaluated with respect to all criteria or some can be skipped (i.e., not considered) if an expert regards them unimportant.	Yes	Yes	Yes	Yes	No
7	Impact of the minimization or maximization of the attributes on the decision-making process	No	Yes	No	No	No
8	Method itself calculates the weights of the attributes	Yes	No	Yes	Yes	Yes
9	Method itself ranks the alternatives	Yes	Yes	No	Yes	Yes
10	Method itself involves group decision making	Yes	Yes	Yes	Yes	Yes
11	Problem is formulated as a mathematical model	No	No	No	Yes	Yes

3.2. Developing A Model for Energy-Sustainable Renovation of Multi-Family Buildings

The ESR of the residential building envelope is a complex endeavor that calls for careful planning and participation of all important stakeholders in order to achieve the project's sustainability goals. Different variant solutions must be designed and considered in order to arrive at a solution that will satisfy various tenants' needs and investors' requirements/constraints. The diagram in Figure 1 presents a model based on a multi-criteria analysis method, the AHP method, which allows a complex problem to be broken down into smaller structured parts to facilitate problem solving and proper consideration of all influencing factors.

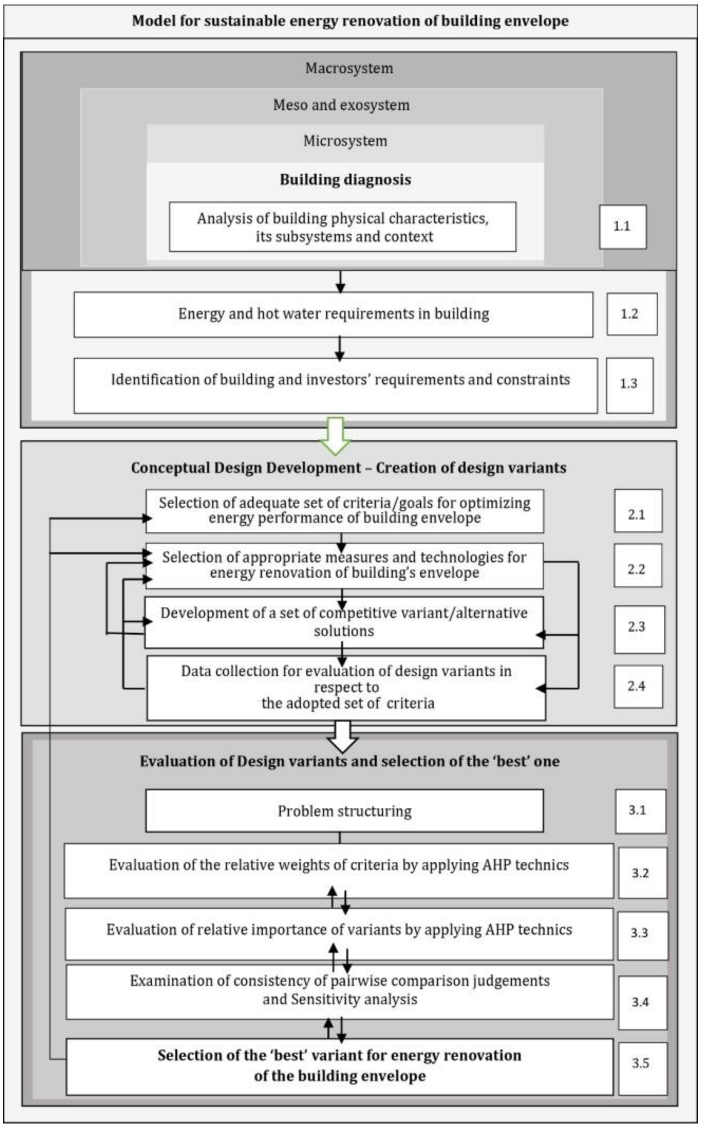

Figure 1. Diagram of the AHP model for energy-sustainable renovation of the building envelope.

3.2.1. Building Diagnosis—Phase I

The diagram in Figure 1 is comprised of three phases. The first step of the proposed model involves the analysis and evaluation of the existing state of the building, specifically, the following elements:

(a) characteristics of the building including thermal and acoustic comfort, the types and the current state of materials used for the building facade and roof, types of materials and load capacity of structural elements, the current state of windows, balconies, etc., [72,73]; (b) the current state of the building's subsystems (the heating and cooling system, hot water system, air-conditioning system, etc.); and (c) characteristics of the building's surrounding (climate at the building's location, shadings of the building, style and types of other buildings in the quarter, solar irradiance, average number of sunny days per year, etc.).

The second step in this phase is to determine the current and future energy and hot water needs of the tenants. This requires a proper assessment of the remaining lifetime of the building, the market demand for housing in the area, the daily and monthly energy needs of the tenants, the uniformity of the demand throughout the year, etc. In addition, the building's constraints, such as structural, aesthetic, and urban planning constraints, together with financial constraints of the investors, also need to be properly assessed, and this is done in the third step in this phase (Figure 1). Moreover, the parameters such as energy and water requirements, building aesthetics and subsystems, and maintenance issues need to be considered at different levels, i.e., micro-system (living unit, apartment, building), meso- and exo-system (housing block, immediate neighborhood, support services), and macro-system (wider neighborhoods, infrastructure systems, city), in order to achieve compliance and harmony between the abovementioned levels of the built environment and ensure appropriate quality and connectedness of the spatial systems.

3.2.2. Development of Conceptual Solution/Generation of Design Variants—Phase II

The first step in the second phase 'Conceptual Design Development' (Figure 1), is to define the objectives for the renewal of the building envelope, considering tenants' energy needs, the building's constraints, and investor's financial capabilities/limitations. These objectives become the criteria in selecting the optimal variant solution when applying the proposed AHP technique; phase III in Figure 1. In addition to economic criteria, environmental and aesthetic criteria are also important in defining and selecting the 'best' solution. They should be defined in accordance with investors' system of preferences and objectives as well as in compliance with the applicable government regulations and standards.

The next step in this phase (step 2.2 in Figure 1) is the selection of adequate measures to improve thermal performance of both see-through and non-transparent parts of the building envelope and the use of renewable energy technologies, i.e., various types of photovoltaic (PV) systems and/or solar water-heating systems (SWHSs), to produce energy on-site if the building's characteristics and its context allow it. This is a very challenging and complex task, especially if solar PV or solar thermal collectors (STCs) are to be implemented on facades. An iterative procedure is proposed to correctly position the solar panels to meet energy, functional, and aesthetic requirements/criteria.

The extent to which solar panels will be effective largely depends on the shading in the building's surroundings and orientations of the respective façade walls/roofs. South, south-west, and south-east orientations, with small or negligent shading, generally allow PV systems and STCs to perform to their highest potential. The roofs are also more convenient for PV systems and STCs in a city environment given that buildings packed against each other and urban greenery are a source of shading [72]. The decision on where to place solar photovoltaics and STCs is made after considering the characteristics of the building, the surroundings, and the climatic characteristics of the area, and the designer's creativity also plays a role in the process. Commonly, the convenient locations are the balconies, parapets, railings, and solar shading fittings, as well as new cladding fixtures mounted over the existing facades, or even solar panels mounted over existing roofs [74]. Other factors to be taken into account are the mounting option and the STCs' tilt angle on the building envelope, since they impact the STCs' efficiency [75,76], as well as the building's functionality and aesthetics. Different design options are compared against the set energy savings objectives, preferably using tailored computer programs that facilitate making optimizations, e.g., in dimensioning of solar PV and STC area, storage tank volume, and other SWHS elements such as the pump, controller, heat exchanger, and auxiliary heating system [77,78], to achieve better thermal energy production, water heating, air conditioning, etc. The number of design variants depends on the set of requirements that must be met, as well as the characteristics of both the building and the PV and SWHS type, their availability in the market, and the designer's resourcefulness [72,78]. The project requirements that usually need to be met include '2030 climate and energy targets' (i.e., minimum level of improvement in energy efficiency, minimum level of reduction in greenhouse gas emissions, minimum share level for renewable energy, etc.), system reliability, and requirements related to system quality and durability.

3.2.3. Assessing and Shortlisting Design Variants—Phase III

The analytic hierarchy process (AHP) [79] is recommended in the decision maker's preference modeling (i.e., the assignment of criteria weights) as well as for the assessment of different designs and selection of the optimal one in the proposed model for ESR of the building envelope. In this technique, the processes of evaluation of variants (alternatives) and aggregation are unified [80] in order to select the most relevant (i.e., the 'best') variant. The ranking/selection is guided by the overall goal, which is decomposed into a set of criteria. The AHP methodology brings together quantitative and qualitative criteria in a single decision-making framework. This characteristic makes the technique suitable for the evaluation of many real problems. In addition, AHP has particular application in group decision making [81]. It is most useful where 'teams of people are working on complex problems, involving human perceptions and judgments, whose resolutions have long-term consequences' [80,81]. It has proved effective for tackling significant aspects that are difficult to quantify or compare [80]. Given that the decision maker is usually an entity, i.e., a group of individuals, its preference and decision-making structure are rather complex. The AHP methodology was chosen for these reasons and incorporated into the proposed model for ESR of the building envelope, to accomplish the following two tasks.

The first task consists of determining the importance weights to be assigned to the criteria in order to achieve the overall objective in an optimal way. This is done by comparing the criteria in pairs keeping in mind the overall goal. The comparative judgement is presented on a semantic scale defined by Saaty [79], which grades importance, including the assignment of a numerical integer value (Table 1) [80,82]. The relative importance of the criterion i over criterion j, designated as a_{ij}, $i = 1, 2 \ldots, n$, $j = 1, 2, \ldots, n$, is then defined/specified by satisfying the reciprocal symmetry condition $a_{ji} = 1/a_{ij}$, for i different from j and $a_{ii} = 1$, $i = 1, 2, \ldots n$. The reciprocal pairwise comparison matrix is then defined as $A = [a_{ij}]_{nxn}$.

The weights of the criteria are then estimated by finding the principal eigenvector W of the matrix, i.e.,

$$A \times W = \lambda_{max} \times W \quad (1)$$

where $\times$ denotes the matrix product, λ_{max} represents the largest eigenvector of the matrix $A = [a_{ij}]_{nxn}$, and the corresponding eigenvector W contains only positive entries as the desired weights. After normalization of the vector W, it becomes the vector of priorities of the criteria with respect to the overall goal [83,84]. The methodology also incorporates the established procedures for checking the consistency of the judgments provided by the decision maker by introducing the measure 'Consistency Ratio' (CR), [83].

The second step in the application of the AHP methodology is the evaluation of the weights of alternatives i, $i = 1, 2, \ldots, m$, with respect to each criterion k, $k = 1, 2, \ldots, n$. A similar procedure is applied as described above. The pairwise comparisons are now based on how much more important alternative i is than alternative j with respect to criterion $k = 1, 2, \ldots, n$, i.e., as elements a_{ij}^{k}. The pairwise relative importance, a_{ij}^{k}, is quantified by using the nine-point scale defined by Saaty that is shown in Table 1 [80,82], as well as the reciprocal symmetry condition. Then, the overall weights of alternatives are computed by using the weighted summation, i.e.,

$$a_i = \sum_{k=1}^{n} a_{ik} w_k,\ i = 1, 2, \ldots m,\ \sum_{k=1}^{n} w_k = 1 \quad (2)$$

where a_i represents the overall weight of alternative i, a_{ik} is the weight of alternative i with respect to criterion k, and w_k is the weight of criterion k with respect to the overall goal.

To correctly apply the AHP methodology, the first step in this phase (step 3.1 in Figure 1) is to decompose a concrete problem into levels, each with a set of hierarchically controlled elements (criteria, sub-criteria, and alternatives) in a top-down direction, allowing their evaluation in pairs with respect to the element directed at a higher level [84]. The AHP keeps all parts of the hierarchy in a relationship, making it clear how changes in one element affect the other elements. Figure 2 illustrates the general structure of the problem for selecting the 'best' alternative.

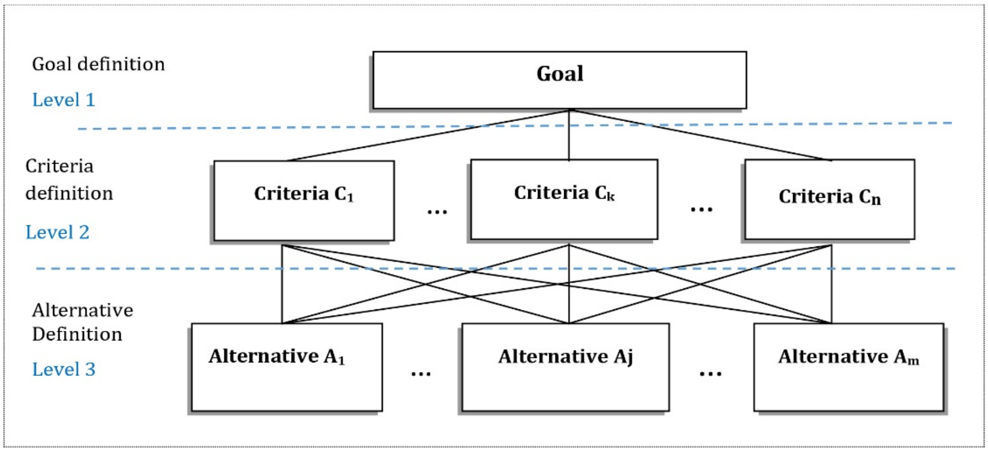

Figure 2. The general structure of the AHP methodology for opting for the 'best' alternative.

The first level of the structure is the definition of the highest (overall) goal. It represents the purpose of the problem solution. The second level of the structure represents a set of criteria against which alternatives are assessed. When it comes to the ESR of the building envelope, economic and technological criteria should be also considered in addition to the principal energy and environmental criteria. On the bottom of the structure we find the alternatives (i.e., different design solutions of the building envelope that need to be evaluated (Figure 2)).

Once the hierarchy has been constructed, decision makers systematically evaluate various elements of the AHP structure by comparing them with each other, in pairs, while assessing their impact on the element preceding them in the hierarchy (Figure 2 and step 3.2 in Figure 1). Decision makers make comparisons using specific information about the elements or their personal judgment about the weight of each element in the whole structure and may also rely on personal judgement in preferring, e.g., alternative *i* in relation to alternative *j*. AHP puts human judgements, and not just the relevant information, at the core of the evaluation process [85]. AHP converts evaluations into numerical values to be further processed and compared. A numerical weight or priority is derived for each element in the hierarchy, which allows for a well-informed and rational comparison of heterogeneous elements [81]. This is a unique feature of AHP that sets it apart from other decision-making techniques.

In the final stage of the evaluation process (step 3.3 in Figure 1), numerical priorities are calculated for each of the alternative decisions. The relative ability of the alternatives to achieve the decision objective is thus numerically expressed [84] and the alternative with the highest value represents the 'best' alternative according to the adopted set of criteria and the decision maker's priority system, which is reflected in criteria weights (step 3.4 in Figure 1). Since the comparisons are undertaken using a subjective approach, some inconsistency may occur. To ensure that the judgement is consistent, the consistency ratio (CR) should be calculated, which will show the consistency between the pairs compared. The consistency ratio (CR) is determined by the ratio of the consistency index (CI) to the random index (RI) [79,83]. Its calculation is explained in detailed in [77]. If the consistency ratio CR < 0.1, the comparison matrix is consistent. Saaty in [79,83] suggests that if CR exceeds 0.1, the set of judgments may be too inconsistent to be reliable. A consistency ratio of zero implies perfectly consistent judgements.

In a model constructed using AHP, sensitivity analysis is a crucial step in determining if the solution is implementable and robust. Such an assessment is undertaken by changing the criteria weight values and calculating the new solution. This so-called One-At-a-Time (OAT) method operates by slightly changing one parameter at a time, calculating the new solution, and graphically presenting how the overall ranking of alternatives consequently changes. Here, the global priority ranking is a function of the global weights of alternatives, which themselves are a linear function of the local contributions, as shown in Equation (2). A desirable sensitivity property is that small local changes in criteria weight values result in very small changes (if any) in the global priority ranking of alternatives.

In the following section, the practical application of the proposed model for ESR on a real building located in the suburb of 'Konjarnik' in Belgrade is presented and all steps are described in detail.

4. Case Study: Sustainable Energy Renovation of the Building Envelope in "Konjarnik" Settlement

4.1. Building Diagnosis

The proposed AHP model is applied to sustainable energy envelope renewal in residential buildings in the Belgrade suburb of 'Konjarnik' (Figure 3), dating from the post-WWII period. At that time, new units had to be constructed rapidly, but the prefabricated construction was in a nascent stage, so the newly built suburbs consisted mainly of typical buildings. An exemplary 'Konjarnik' building is shown in Figure 4, and was taken for the case study. It is a typical eight-story building (ground floor, six floors and attic), including five lamellas. The building is located in a half-closed block, on a south-oriented hillside. For the analysis, one of the central lamellas was selected, and its appearance is shown in Figure 5. Each lamella has a typical floor layout with four one-side-oriented flats; the bigger flats are south-oriented and two smaller flats are north-oriented. The lamella has the following characteristics: width = 13.30 m, length = 25 m, height = 22.60 m, heated floor area = 242 m^2, heated building area = 1938 m^2, and heated building volume = 5470 m^3. The surface of the thermal envelope amounts to 2177 m^2, which includes the south facade of 493.5 m^2, the north facade of 493.5 m^2, the surface of 332.5 m^2 facing the ground and the same surface of the attic, and the total area of 525 m^2 toward adjacent lamellas. The facades consist of rows of windows and parapets, or windows and loggias (Figure 5). The total area of parapet walls is 352.8 m^2, while the window glazing amount is 357.8 m^2 and the loggia glazing amount 257.6 m^2.

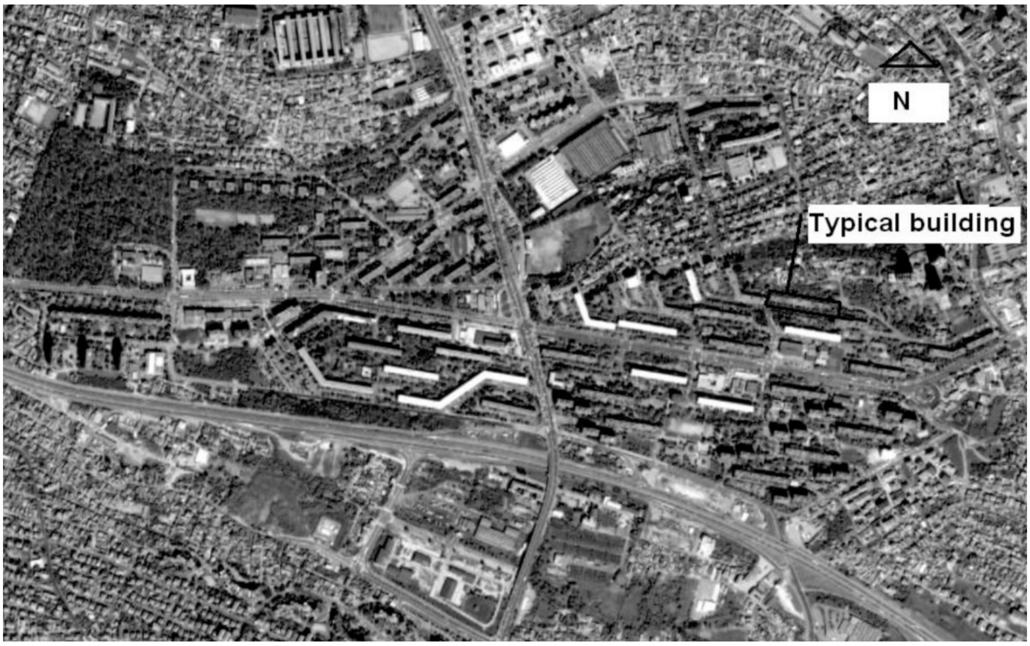

Figure 3. Building layout in 'Konjarnik' settlement, Belgrade [72].

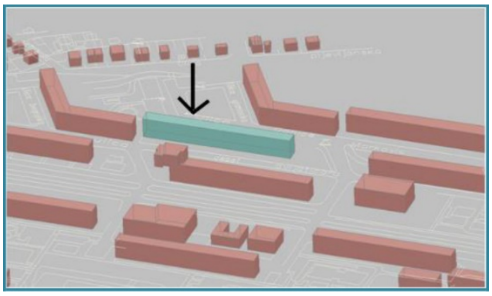

Figure 4. Position of the building (taken as a case study) in the suburb 'Konjarnik' [86].

Figure 5. Appearance of the typical building in the settlement of 'Konjarnik' [87].

The data on thermal energy consumption in the building were taken from the official data of the company 'Belgrade Thermal Power Plant', which provides heating to the 'Konjarnik' settlement. The data on electricity consumption for water heating are based on actual tenants' water consumption, and were also taken from the official data of the company 'Belgrade Waterworks and Sewerage'. Water consumption amounts to 7200ℓ (20–50 °C) per day for one lamella. Energy consumption was 251 kWh per day, or 91,618.3 kWh per year, for one lamella.

The project restriction, defined by the building maintenance manager/administrator, was related to the simple payback period for total investment cost, which was limited to a maximum of 15 years. The total investment cost (STCs + installation + other) was also limited and amounted to EUR 350,000 [86,88–90].

4.2. Conceptual Design Development—Creation of Design Variants

As suggested in the proposed model (step 2.1, Figure 1), in order to appropriately generate the variant solutions/alternatives for a building's ESR, it is first necessary to define the criteria against which the variant solutions will be evaluated. Generally, the criteria are defined in consultation with decision makers. In the presented case study, the decision makers are as follows: (a) apartment owners (represented by the building administrator/manager; (b) the government; specifically, the government in cooperation with local municipality subsidizes the renovation projects for building energy efficiency and installation of solar collectors, heat pumps, etc., through the model of public–private partnership (50/50%); and (c) the European Bank for Reconstruction and Development (EBRD) since Serbia is a part of the Green Economy Financing Facility (GEFF) program for the Western Balkans, which supports energy-efficient solutions in the residential sector to build a greener and more sustainable economy. The program is supported by the EU, the Western Balkans Investment Framework (WBIF), and the Austrian Federal Ministry of Finance, with the fund of EUR 11 million provided the European Bank for Reconstruction and Development (EBRD).

Given that the study considers the initial phase of the renovation project, i.e., 'Development of conceptual solutions and preliminary feasibility studies', the initial decision about the initiation of the project is made by only one decision maker—the apartment owners. After reviewing the feasibility study, which includes conceptual solutions/alternatives, initial project costs, energy savings, investment payback period, project implementation time, etc., an informed decision is made about whether to proceed with the project. In the case of a positive decision, the opinions of the other above-mentioned decision makers on the weight structure of the criteria are taken into account, and comparison matrices of criteria are formed. In this stage, introduction of new criteria is also considered in order to satisfy all the necessary requirements of other decision makers and ensure the financial support of the project.

For the selected case study, in consultation with the building administrator, the following criteria are selected:

(1) Energy consumption for space and water heating (C1) per one year;
(2) CO_2 emissions (C2) per one year;
(3) Investment costs of envelope energy renovation (C3);
(4) Payback period (C4).

As can be noted, two economic criteria and two criteria relating to the environmental aspect of sustainability were defined. They are explained and discussed in Section 4.3.

In the next step (step 2.2 in Figure 1), the proposed model envisages defining measures by which the energy performance of the building envelope can be improved. For the given case study, these measures include improving the thermal performance of the parts of the building envelope made of see-through materials, as well as the non-transparent parts, and the use of renewable energy sources by implementing a solar water-heating system (SWHS). The decision to implement the SWHS system was based on the fact that the requirements for hot water consumption were quite high, so implementing a system capable of using a renewable energy source would save a significant amount of energy from fossil fuels and consequently have a positive impact on the environment by reducing CO_2 emissions. The measures for improving the thermal envelope performance were the following:

(a) Increasing the quality of thermal insulation on the parapet wall and attic slab, including thermal bridges;
(b) Complete replacement of the windows with cutting-edge solutions with improved thermal and solar radiation characteristics;
(c) Glazing of loggias.

Accordingly, insulation systems M1 and M2 were defined for the thermal improvement of the building envelope and are presented in Table 2. They differ in terms of the thickness of the parapet and attic slab insulation, as well as in types of glazing in windows and loggias; see Table 2. Their annual primary energy consumption (APE) for heating, compared to the current state of APE consumption [81], is presented in the diagram in Figure 6. As can be seen from the diagram, the annual energy savings are significant and amount to 89.5% and 94.8% for the M1 and M2 insulation systems, respectively, compared to the existing energy consumption (Figure 6).

The decision to implement the SWHS system was based on the two following fundamental reasons: (1) the water and sewage system was dilapidated (more than 60 years old) and needed to be replaced and (2) the hot water demand was quite high (i.e., 251 kWh per day, or 91,618.3 kWh per year for a lamella) and relied on a liquid-oil-based water-heating system. Thus, implementing a system capable of using a renewable energy source would save a significant amount of energy from fossil fuels and have a positive impact on the environment by reducing CO_2 emissions.

With regard to the implementation of the SWHS, four options for placing solar thermal collectors on the building envelope were shortlisted as competitive solutions according to energy, functional, economic, and aesthetic criteria (Figures 7 and 8). The adequate positioning of solar panels on the building envelope is a complex issue and requires special analysis to meet energy, functional, and economic requirements on the one hand, and aesthetic criteria on the other. It has been analyzed in detail by the authors and described in previous studies [72,74,86]. The tilted angles of 40°, 90°, 45°, and 0° were selected as being optimal, after the assessment of factors such as functionality and aesthetic appearance, mounting ease, and the adjustment to the local climate. Several variants were designed and tested based on the criterion 'Optimal ratio between hot water production and STC area' (called RW,A), and its value was set at RW,A 70 L/m^2 [80]. Only those variants that created aesthetically harmonic glazed surfaces on the existing walls, parapets, and balconies, and at the same time met the criteria of RW,A, were considered suitable. The type, GFP STC [83], was selected as the most adequate for all variant solutions, due to the climatic conditions in Belgrade. Considering their good aesthetic characteristics and the ability to deliver custom products on time and at a reasonable price, Doma flek Alu STCs from Austria's AKS Dom [91] were chosen as the most appropriate type of solar thermal collector (STC). This solution assumes a tank volume of 14,400 L, which is twice the average daily consumption of hot water [89]. For all selected variants for mounting the STCs, metal profiles provided by the manufacturer were used.

The four selected variants of different STC positioning (Figures 7 and 8), the tilt angle, and the total area of the STCs were as follows:

1. STC Variant I: STCs mounted on the roof and tilted by 40°, area of 100 m^2 (Figures 7a and 8a);
2. STC Variant II: STCs integrated into the parapets (vertical position, tilted by 90°), area of 90 m^2 (Figures 7b and 8b);
3. STC Variant III: STCs integrated into the parapets and tilted by 45°, area of 120 m^2 (Figures 7c and 8c);
4. STC Variant IV: STCs integrated as sun shadings (horizontal position, tilted by 0°), area of 55 m^2 (Figures 7d and 8d).

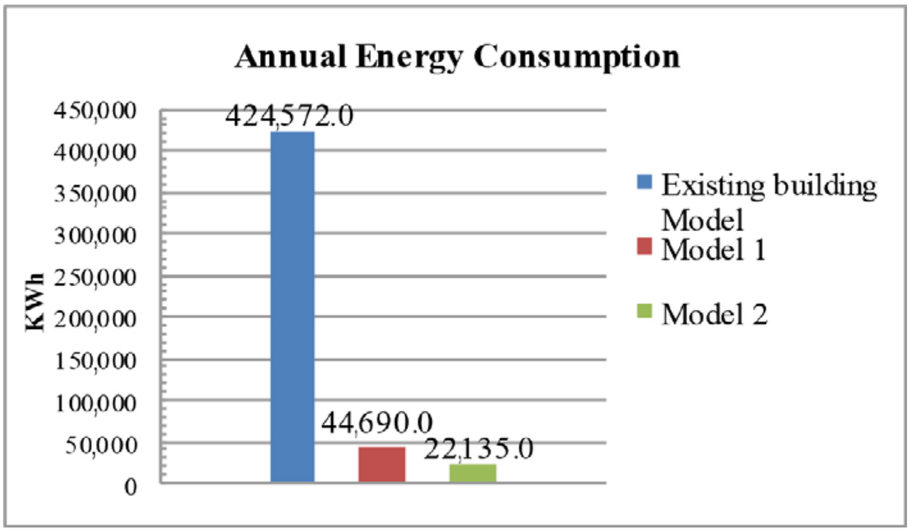

Figure 6. Comparison of per annum primary energy consumption for heating of the M1 and M2 Insulation systems with existing energy consumption [87].

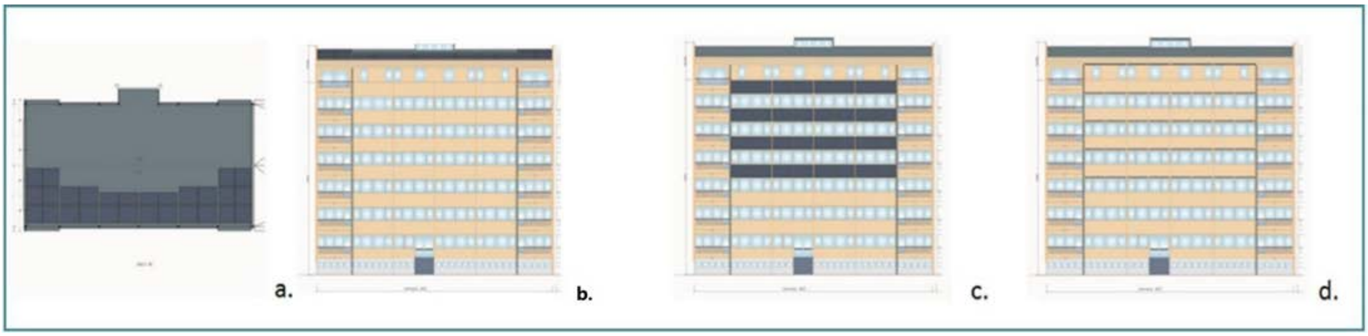

Figure 7. Design variants of the position of solar thermal collectors on the building envelope: (**a**) STC Variant I; (**b**) STC Variant II; (**c**) STC Variant III; (**d**) STC Variant IV, [87].

Their thermal energy production in relation to the total annual energy demand for water heating and the percentage satisfaction of the energy demand for water heating per month were analyzed by the authors in [87], and the values are presented in the diagrams in Figures 9 and 10.

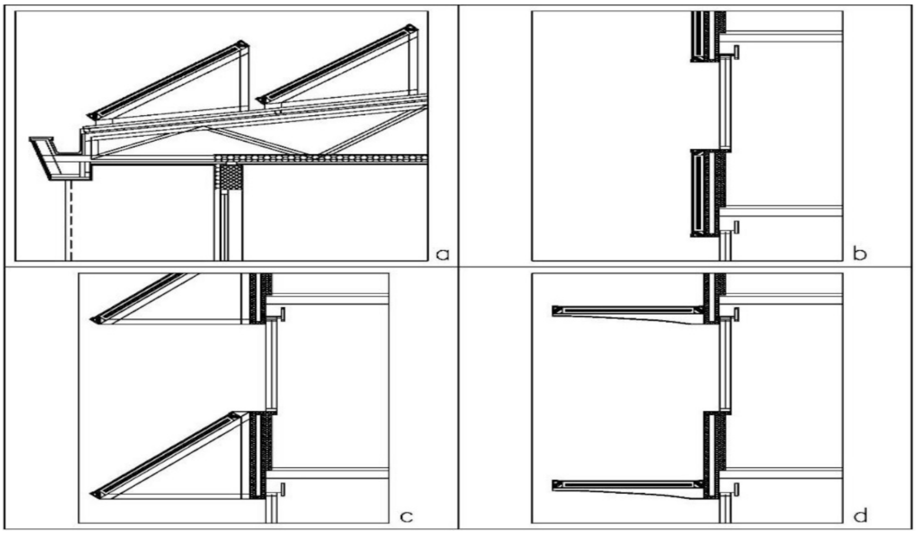

Figure 8. Cross-sections of design variants: (**a**) STC Variant I; (**b**) STC Variant II; (**c**) STC Variant III; (**d**) STC Variant IV, [87].

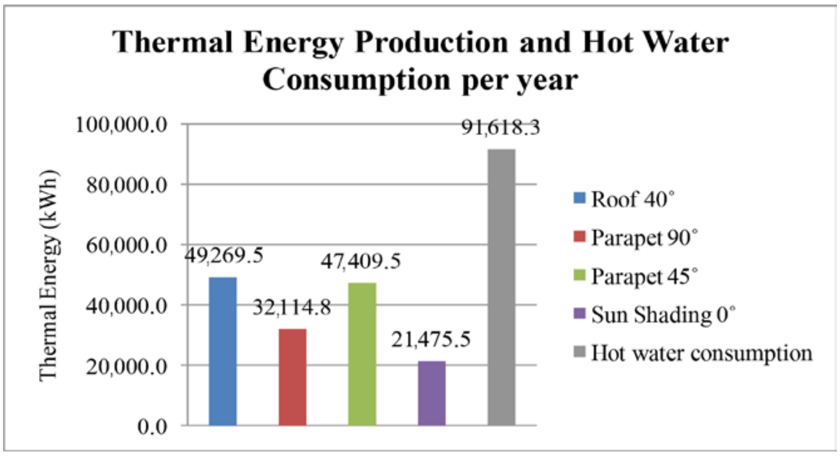

Figure 9. Annual thermal energy production by four STC variants and current energy consumption for water heating [87].

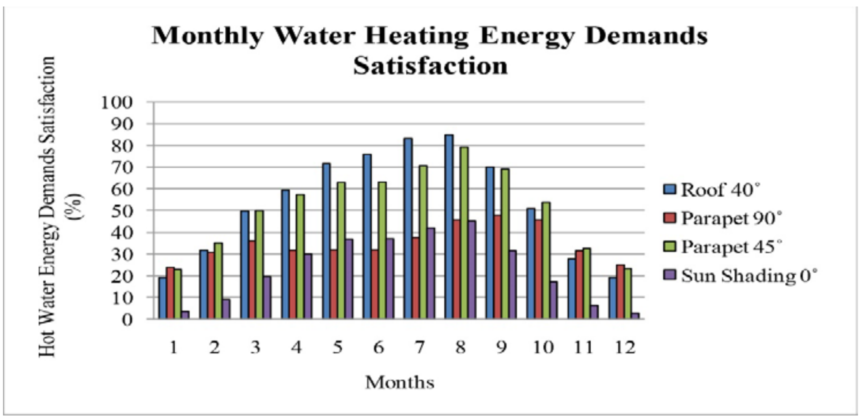

Figure 10. Percentage satisfaction of the energy demand for water heating per month [87].

Since the proposed insulation measures to improve the thermal efficiency of the building, the M1 and M2 insulation systems (Table 2), can be applied in combination with any of the presented STC variants (Figures 7 and 8), we thus obtained eight different alternatives for improving the energy efficiency of the building envelope. These alternatives are described in Table 3, while their annual energy consumption and the corresponding savings for space and water heating are shown in Table 4. As can be seen from Table 4, the primary energy savings for the alternatives considered are significant and vary from 83% to 96% depending on the type of insulation system applied (system M1 or M2), and the location of the STCs on the building envelope and their implemented total area.

Table 3. Saaty's Ratio scale for pairwise comparison of importance weights assigned to criteria and alternatives.

Intensity of Importance	Definition	Description
1	Equal importance	Two criteria or alternatives equally contribute to the objective
3	Moderate importance	Experience and judgment slightly favor one over the other
5	Strong importance	Experience and judgment strongly favor one over another
7	Very strong importance	An element is strongly favored and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is one of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	

Table 4. Insulation systems M1 and M2 for improving thermal efficiency of the building envelope.

System of Thermal Improvement	PARAPET WALLS (315 m^2)		Attic Slab (310 m^2)		GLAZING (593 m^2)				Predicted Exchanges of the Air Flow
					Windows (329 m^2)		Loggias (268 m^2)		
	Wall Structure South—(157.5 m^2) and North—(157.5 m^2) Oriented Parapet Walls)	U-Value [W/m^{2}K]	Thickness of Thermal Insulation	U-Value [W/m^{2}K]	Type of Glazing and Profiles	U-Value [W/m^{2}K]	Type of Glazing and Profiles	U-Value [W/m^{2}K]	
Insulation System M1	Internal concrete 10 cm, thermal insulation 5 cm, external concrete 5 cm + 5 cm added expanded polystyrene total TI thickness = 10 cm	0.371	10 cm of added hard mineral wool resulting in 22 cm of thermal insulation	0.171	Double glazing (4 + 12 + 4 mm) laid in five-chamber PVC profiles	2.30	Double glazing (4 + 12 + 4 mm) laid in five-chamber PVC profiles	2.30	2–3
Insulation System M2	Internal concrete 10 cm, thermal insulation 5 cm, external concrete 5 cm + 10 cm added expanded polystyrene total TI thickness = 15 cm	0.255	10 cm of added hard mineral wool resulting in 22 cm of thermal insulation	0.171	Low-emission glazing with argon filler laid in five-chamber PVC profiles	0.90	Double glazing (4 + 12 + 4 mm) laid in five-chamber PVC profiles	2.30	0.8–1

All data required for the calculation of the annual energy consumption for the considered alternatives A1 to A8, as well as the data for calculation of other three criteria functions (i.e., C2, C3, C4), were collected by the authors and presented in [87,89,92], while their final results are shown in Table 5. In this way, the last stage of phase 2 of the proposed model (phase 2.4 in Figure 1) was completed, thus allowing the application of the AHP technique to rank the alternatives (phase 3 in Figure 1) and, consequently, the selection of the best alternative to improve the energy performance of the building envelope. The description of phase 3 is given in the sub-Section 4.3.

Table 5. Description of alternative solutions A1 to A8 for energy improvement of the building envelope.

Alternative	Type of Insulation System	Roof Collectors	Façade Collectors
A1	Insulation System M1	Roof Collectors with area of 100 m^2 and tilted by 40°	-
A2	Insulation System M1	Roof Collectors with area of 100 m^2 and tilted by 40°	Façade Collectors with area of 90 m^2 and tilted by 90°
A3	Insulation System M1	Roof Collectors with area of 100 m^2 and tilted by 40°	Façade Collectors with area of 120 m^2 and tilted by 45°
A4	Insulation System M1	Roof Collectors with area of 100 m^2 and tilted by 40°	Façade Collectors with area of 145 m^2 and tilted by 90° + Sun shading 0°
A5	Insulation System M2	Roof Collectors with area of 100 m^2 and tilted by 40°	-
A6	Insulation System M2	Roof Collectors with area of 100 m^2 and tilted by 40°	Façade Collectors with area of 90 m^2 and tilted by 90°
A7	Insulation System M2	Roof Collectors with area of 100 m^2 and tilted by 40°	Façade Collectors with area of 120 m^2 and tilted by 45°
A8	Insulation System M2	Roof Collectors with area of 100 m^2 and tilted by 40°	Façade Collectors with area of 145 m^2 90° + Sun shading 0°

4.3. Discussion on Criteria and Alternatives

The first criterion ('*Annual energy consumption for space and water heating*') is a basic indicator of the building's energy needs, and is directly related to the quality of the insulation system applied in the building envelope and the needs of the tenants. Since different variants of insulation systems are examined, this criterion is suitable for evaluating alternative insulation systems/solutions. In addition to the total annual consumption, for accurate calculation of the required area of the STC, it is necessary to estimate monthly and daily energy needs of the building, since they vary across different months, as well as during the day. (For example, space heating requirements are much higher in winter than in spring and fall, or in the evening compared to other times of the day). Design variants should also be tested for these sub-criteria in order to effectively meet the energy needs of the tenants. The second criterion ('Annual CO_2 emission') is a common environmental criterion and serves to evaluate the reduction in CO_2 emissions through replacement of fossil fuels with clean renewable energy sources. The 'Investment costs of envelope energy renovation' and 'Payback period' are usually the most significant economic criteria for investors because they are related to the initial investment cost of the renovation project and the investment recovery period. In developing countries such as Serbia, due to their difficult economic situation, these economic criteria are of significant importance, because apartment owners (i.e., investors in residential buildings) are in most cases ordinary citizens whose average incomes are very low. Therefore, both criteria play an important role in decision making.

Two different insulation systems (system M1 and M2) were designed as variant solutions for insulating the building envelope. The M1 system envisages double glazing (4 + 12 + 4 mm) laid in five-chamber PVC profiles both for windows and loggias (a total area of 268 m^2), while the M2 system for windows includes low-emission glazing with argon filler laid in five-chamber PVC profiles, and for loggias includes the same type of glazing as in the M1 system (i.e., double glazing (4 + 12 + 4 mm) laid in five-chamber PVC profiles. The type and thickness of the thermal insulation of the attic slab (a total area of 310 m^2) was envisaged to be the same for both insulation systems (the systems M1 and M2), i.e., 10 cm of hard mineral wool was added, resulting in a total thickness of 22 cm of thermal insulation for the attic slab.

As can be seen from Table 3, the alternative A1 includes the insulation system M1 and STC of 100 m^2 installed on the roof of the building, while the alternatives A2, A3, and A4, in addition, include the installation of an STC on the facade of different surfaces (90 m^2, 120 m^2, 90 m^2 of facade collectors + 55 m^2 as sun shadings, respectively), and at different angles (90°, 45°, 90°+ sun shading at 0°, respectively); see Table 3 and Figures 7 and 8. Figure 9 shows their energy production, which varies depending on the position of the STCs on the building envelope, the total area of the STCs, and their tilt angle. The alternatives A5, A6, A7, and A8 fully correspond to alternatives A1, A2, A3, and A4 in terms of STC installation, but contain the M2 insulation system instead of the M1 system; see Table 3. Therefore, the insulation characteristics, energy production capacity, and initial investment costs for the presented design alternatives are different and need to be evaluated with respect to the given set of criteria defined by the decision maker.

For the selection of the 'best' alternative, the AHP method is proposed to solve this type of MCDM problem. Its procedure is described in sub-Section 4.4

4.4. Evaluation of Design Variants and Selection of the Best One—Phase III

The first step in this phase involves problem structuring. Figure 11 illustrates the structure of the building energy improvement problem for the selected case study 'Konjarnik'. As can be noted from Figure 11, the criteria C1 to C4 are presented on the second level of the hierarchy structure and the alternatives A1 to A8 on the third.

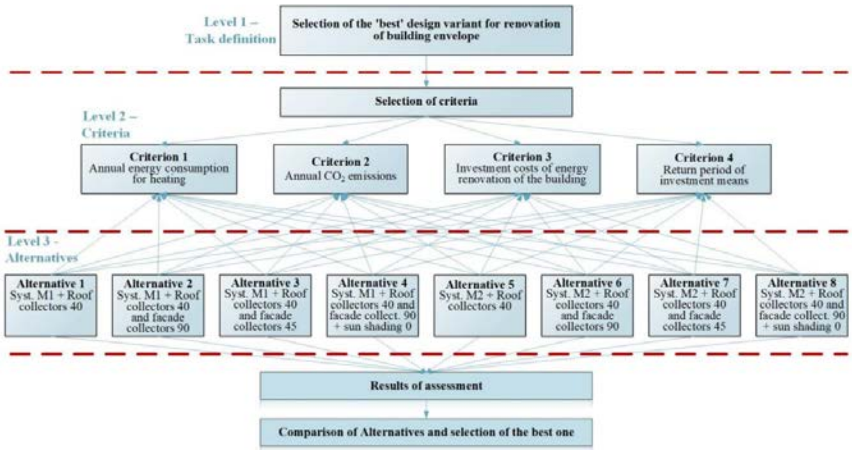

Figure 11. Structure of the building energy renovation problem for the selected case study 'Konjarnik'.

For the establishment of criteria weights, the first step was comparing the criteria in pairs with regard to the overall goal. For the presented case study, the pairwise comparison of the criteria was undertaken by the apartment owners as follows. The building administrator, elected by the assembly of apartment owners, by using semantic judgements (equally important, moderately important, more important, etc., to extremely important) counted the votes of the owners for each semantic assessment for the offered pair of criteria, and the assessment that received the highest number of votes was taken as the final value of the assessment for the considered pair of criteria. The same procedure was repeated for each pair of criteria. Then, the judgements were transferred into Saaty's Ratio scale (Table 1) to form the criteria comparison matrix A. The decision maker (i.e., the apartment owners) gave certain preference to criterion 3 ('Investment cost') over energy and environmental aspects and assigned the least importance to criterion C4 ('Payback return'); see Table 6. All the needed calculations for the criteria weight vector evaluation were performed using the professional software *SuperDecisions* [93]. The results are presented in Table 6 and the graphical representation of the calculated criteria weights is shown in Figure 12.

Table 6. Annual energy consumption and corresponding savings for space and water heating for alternatives A1 to A8.

Alternatives	Description of the Alternatives	Annual Primary Energy Consumption (kWh)			Energy Savings (kWh)	Reduction in Energy Consumption (%)
		For Space Heating	For Hot Water	Total		
	System M of the existing building	424,572	91,618	516,190		
A1	System M 1 + Roof collectors 40°	44,690	42,349	87,039	429,151	83
A2	System M 1 + Roof collectors 40° and facade collectors 90°	44,690	10,234	54,924	461,266	89
A3	System M 1 + Roof collectors 40° and facade collectors 45°	44,690	energy surplus (+5060)	44,690	471,500	91
A4	System M 1 + Roof collectors 40° and facade collectors 90° + sun shading 0°	44,690	energy surplus (+11,242)	44,690	471,500	91
A5	System M 2 + Roof collectors 40°	22,135	42,349	64,484	451,706	88
A6	System M 2 + Roof collectors 40° and facade collectors 90°	22,135	10,234	32,369	483,821	94
A7	System M 2 + Roof collectors 40° and facade collectors 45°	22,135	energy surplus (+5060)	22,135	494,055	96
A8	System M 2 + Roof collectors 40° and facade collectors 90° + sun shading 0°	22,135	energy surplus (+11,242)	22,135	494,055	96

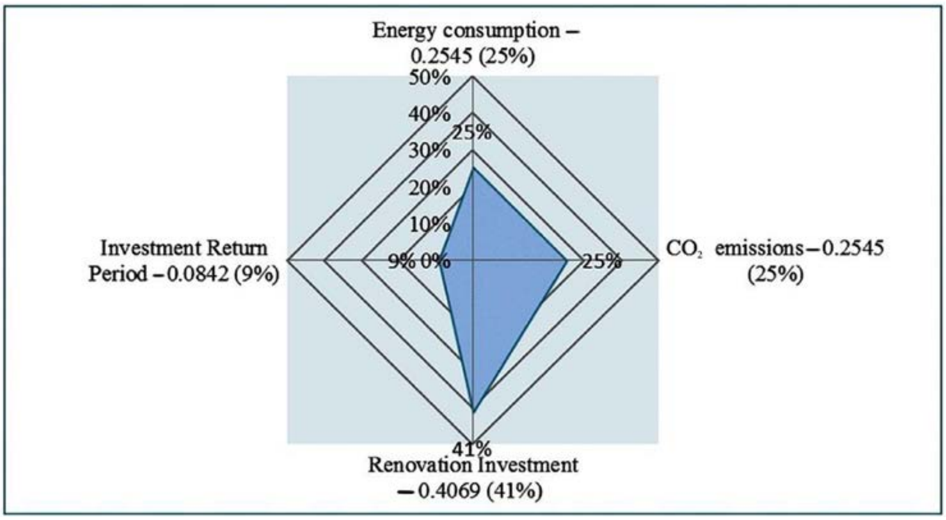

Figure 12. Relation of the weights of the criteria C1 to C4.

The consistency ratio (CR) was also calculated using the same software and satisfied the recommended value of being no greater than 0.10, i.e., C.R. = 0.04591 $\leq$ 0.10 (Table 6), meaning that the pairwise comparisons were consistently performed [83].

The comparison of the alternatives (the third level of the hierarchical structure in Figure 11) was performed by first converting the real calculated values of all criteria functions C1 to C4, given in Table 4, into the Saaty Ratio scale values and then the comparative matrix A of alternatives with respect to each criterion was formed. The same computer software, SuperDecisions version 3.0, was used to calculate the local weight w_i^j (i.e., the weight of alternative i = 1, 2, . . . , 8, with respect to criteria C_j, j = 1, 2, 3, 4). The consistency of all pairwise comparisons of the alternatives was also checked and the calculated value of the consistency ratio (CR) was less than 0.10 for all consistency matrices. The initial matrix of the relative weights of alternatives A1 to A8 is presented in Table 7, and their local weights are shown in Table 8. The overall weights of alternatives, w_i, i = 1, 2, . . . , 8 (calculated as the sum of local weights w_i^j, j = 1, 2, 3, 4, see Equation (2)), are shown in row 5 in Table 8. The priority order of the alternatives is given in Table 9. It is formed based on the decreasing overall weight values.

Table 7. Values of criteria functions F_{C1} to F_{C4} for the selected alternatives A1 to A8.

Alternatives	Description of Alternatives	Criterion C1 Annual Primary Energy Consumption (kWh)	Criterion C2 Annual CO_2 Emissions (kg)	Criterion C3 Investment Costs (EUR)	Criterion C4 Return Period of Financial Investment (Years)
A1	M1 + Roof collectors 40°	87,039	34,064	187,180	7.96
A2	M1 1 + Roof collectors 40° and facade collectors 90°	54,924	17,043	250,180	9.16
A3	System M 1 + Roof collectors 40° and facade collectors 45°	44,690	11,620	271,180	8.55
A4	System M 1 + Roof collectors 40° and facade collectors 90° + sun shading 0°	44,690	11,620	288,680	10.34
A5	System M 2 + Roof collectors 40°	64,484	28,200	211,910	9.03
A6	System M 2 + Roof collectors 40° and facade collectors 90°	32,369	11,179	274,910	10.10
A7	System M 2 + Roof collectors 40° and facade collectors 45°	22,135	5755	295,910	9.35
A8	System M 2 + Roof collectors 40° and facade collectors 90° + sun shading 0°	22,135	5755	313,410	11.25

Table 8. Comparison matrix for the criteria C1 to C4 in relation to the goal.

	C1	C2	C3	C4	Weights
C1	1	1	−2	4	0.2545
C2		1	−2	4	0.2545
C3			1	3	0.4068
C4				1	0.0842
	$\lambda_{\max} = 4.231$ $C.I. = 0.0410$ $C.R. = 0.04591 \leq 0.10$				

Table 9. Initial matrix of relative weights of alternatives in relation to the criteria C1 to C4.

Alternative	Alternative Weights in Relation to Criterion C1	Alternative Weights in Relation to Criterion C2	Alternative Weights in Relation to Criterion C3	Alternative Weights in Relation to Criterion C4
A1	0.05440	0.04007	0.17005	0.14709
A2	0.08621	0.08009	0.12722	0.12782
A3	0.10595	0.11747	0.11737	0.13694
A4	0.10595	0.11747	0.11026	0.11324
A5	0.07342	0.04841	0.15020	0.12967
A6	0.14627	0.12211	0.11578	0.11593
A7	0.21390	0.23719	0.10756	0.12523
A8	0.21390	0.23719	0.10156	0.10408

4.5. Selection of the Most Suitable/Best Alternative for Energy Efficiency Improvement and Sensitivity Analyses

As Tables 10 and 11 show, alternative A7 is the 'best' according to its ranking (i.e., it has the highest overall weight), followed immediately by the alternative A8. Sensitivity analysis was also carried out to check whether the solutions are stable, i.e., whether the ranking order of alternatives changes if the relative criteria weights change [94]. All calculations were carried out using SuperDecisions software. The results show that small changes in the relative importance of the criteria do not have a significant impact on the ranking order of the alternatives. The diagram in Figure 13 presents the sensitivity of the alternatives ranking in relation to the C3 criterion weight changes ('Investment costs'). Figure 13a shows that, as the significance of criterion C3 increases, the rank of alternatives 7 and 8 slowly decreases, while the rank of the other alternatives slowly rises. For preference values of criterion C3 above 70 percent (strong dominance), alternatives A7 and A8 no longer lead the ranking, but alternative A1 takes precedence (Figure 13b). This means that the investment costs of alternatives A7 and A8 are significantly higher than the others, and as the relative weight of this criterion increases, they lose their priority and some other alternatives with lower investment costs become more suitable options.

Table 10. Weighted-normalized decision-making matrix for the alternatives A1 to A8.

Column	Criteria	Criteria Weight (α_i)	C Weight $\times w_1^j$	C Weight $\times w_2^j$	C Weight $\times w_3^j$	C Weight $\times w_4^j$	C Weight $\times w_5^j$	C Weight $\times w_6^j$	C Weight $\times w_7^j$	C Weight $\times w_8^j$	
1	C1	0.2545	0.01384	0.02194	0.02696	0.02696	0.01868	0.03722	0.05444	0.05444	
2	C2	0.2545	0.01021	0.02038	0.02989	0.02989	0.01232	0.03108	0.06036	0.06036	
3	C3	0.4068	0.06918	0.05175	0.04776	0.04485	0.06111	0.04710	0.04375	0.04131	
4	C4	0.0842	0.01238	0.01076	0.01154	0.00955	0.01092	0.00976	0.01055	0.00876	
5	Alternative overall weight (Σ)		0.10561	0.10484	0.11614	0.11125	0.10303	0.12303	0.16910	0.16487	Σ = 1.00
6	Priority order of alternatives		6.	7.	4.	5.	8.	3.	1.	2.	

Table 11. Final priority of the alternatives A1 to A8 according the adopted criteria weights.

Alternatives	Description of Alternatives	Alternatives Overall Weight	Ranking of Alternatives
A1	Insul. System M1 + Roof collectors 40° (STCs area of 100 m^2)	0.10561	6
A2	Ins. System M1 + Roof collectors 40° and facade collectors 90° (STCs total area of 190 m^2)	0.10484	7
A3	Insul. System M1 + Roof collectors 40° and facade collectors 45° (STCs total area of 220 m^2)	0.11614	4
A4	Insul. System M1 + Roof collectors 40° and facade collectors 90° + sun shading 0° (STCs total area of 245 m^2)	0.11125	5
A5	Insul. System M2 + Roof collectors 40°	0.10303	8
A6	Insul. System M2 + Roof collectors 40° and facade collectors 90° (STCs total area of 190 m^2)	0.12303	3
A7	Insul. System M2 + Roof collectors 40° and (STCs total area of 220 m^2) facade collectors 45°	0.16910	1
A8	Insul. System M2 + Roof collectors 40° and facade collectors 90° + sun shading 0° (STCs total area of 245 m^2)	0.16487	2

An analysis of the sensitivity to the change in the weights of the other criteria (C1, C2, and C4) was also performed and no significant changes were found. Furthermore, for any preferred value of the criterion C2 ('Annual CO_2 emissions'), the ranking of the alternatives remained unchanged (Figure 13c).

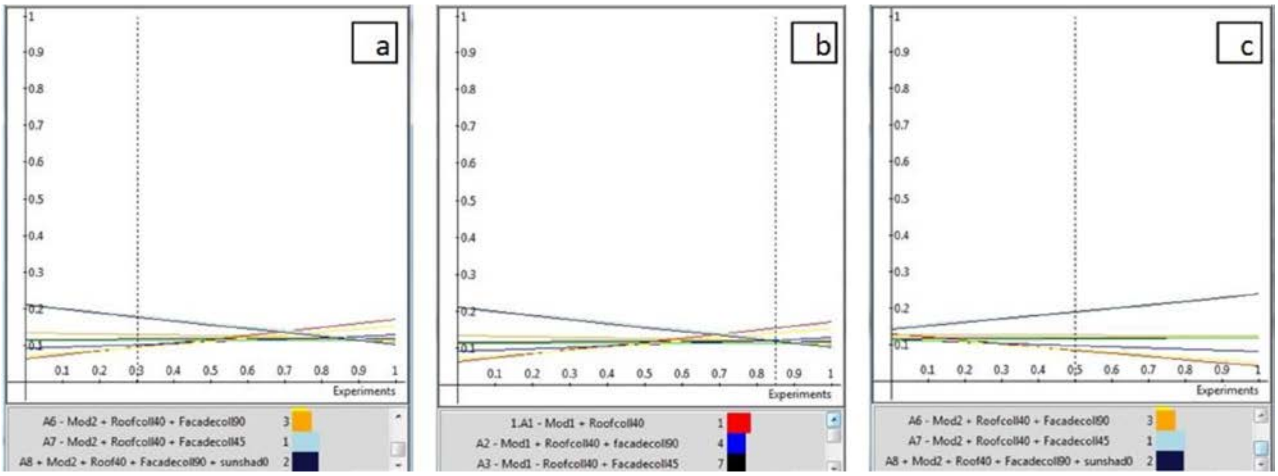

Figure 13. Sensitivity of the solution regarding criterion C3—investment costs: (**a**) as the significance of criterion C3 increases the rank of alternatives 7 and 8 slowly decreases; (**b**) for preference values of criterion C3 above 70 percent (strong dominance),alternatives A7 and A8 no longer lead the ranking; (**c**) for any preferred value of the criterion C2 the ranking of the alternatives remained unchanged.

4.6. Discussion of Results

The results obtained (Table 8 and Figure 14) indicate that the alternative A7 is the most suitable alternative for the building-energy renovation of the presented case study, with regard to the set of adopted criteria and their associated relative weights. The overall weight of alternative A8 is only slightly inferior to the weight of alternative A7, while the third-ranked alternative A6 has an overall weight that is significantly lower than the first two ranked alternatives (with respect to the adopted set of criteria and their associated relative weights); Figure 14. For all three alternatives, STCs are installed on both the roof and the facade walls, but with diverse amounts of STC area and at different tilted angles; therefore, the values of the criterion function differ, favoring the alternatives with larger STC areas. The worst alternative is A5, which includes insulation system M2 and STCs placed only on the roof, reflecting a significantly higher primary energy consumption and thus higher CO_2 emissions (criteria C1 and C2, respectively) compared to all other alternatives.

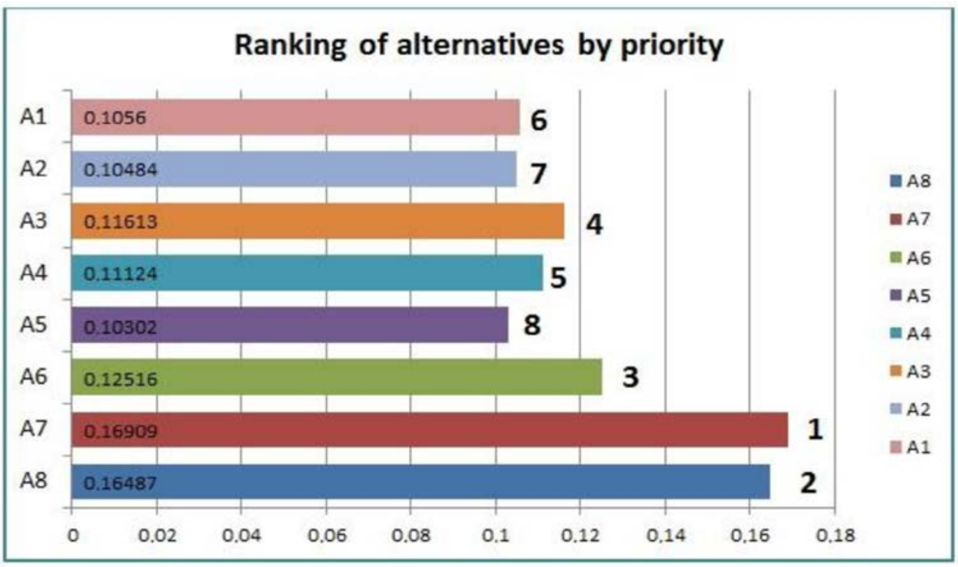

Figure 14. Ranking of alternatives in order of priority.

The results obtained also indicate that the ranking order of alternatives depends on the relative weights of the criteria; Figure 15. By setting relative weights for criterion C3 (initial investment costs) above 0.7, the alternatives A7 and A8 lose their leading position and alternative A1 takes primacy because it is the best with respect to the C3 and C4 criteria, while in alternatives A7 and A8 these values are quite low. The consistency ratio (CR) was 0.0229, and because its value is below 0.1, the result can be considered consistent.

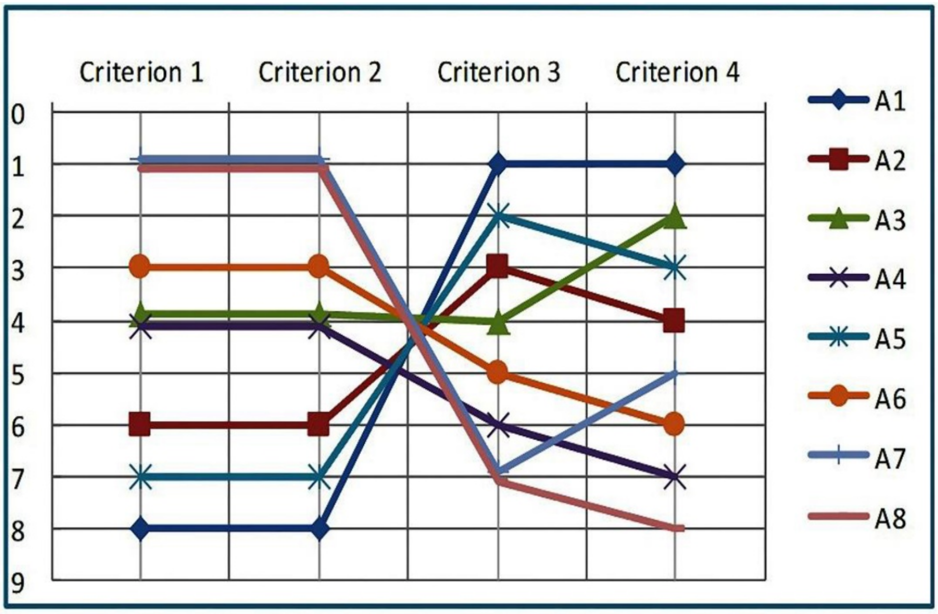

Figure 15. Ranking of alternatives according to individual criteria.

5. Conclusions

Renovation in the construction industry is considered to be the primary area for achieving the goals set by the EU regarding energy and material resource savings, CO_2 emission reduction, increasing the renewable energy share, and improving social sustainability issues [95–101].

This requires a fast transition to renewable and fossil-free energy.

A major contribution to achieving CO_2 emissions reduction is envisaged to come from renovation of the existing building stock by increasing insulation and changing the building services (heating, cooling, ventilation, and electricity) to carbon-free systems [102].

To this end, this article defines a model for energy-sustainable renovation of residential buildings based on a multi-criteria analysis methodology—the AHP method.

The model includes guidelines for defining the renovation goals and the process of designing alternative solutions based on the established existing state of the building, tenants and investors' needs and requirements, as well as the '2030 climate and energy targets' on one hand, and the current and future development conditions of the meso-, exo-, and macro-systems on the other.

An iterative procedure was adopted for the process of designing alternative solutions due to the great complexity of the problem presented by conflicting functional and aesthetic, energy performance, economic, and ecological requirement classes.

The proposed model was applied to solving a real problem—the renovation of the building envelope of residential buildings in the suburb of 'Konjarnik' in Belgrade. A renewable SWHS and an appropriate insulation measure were integrated into the building envelope, enabling significant improvement in the building energy performance and reduction in the environmental impact, i.e., the realization of the '2030 climate and energy targets'.

Among the eight designed alternatives, the first three ranked positions were occupied by the alternatives that include a system with better insulation characteristics (i.e., the insulation system M2), and the STCs integrated both on the building roof and façade. Although they have initial investment costs (criterion C3) that are about 10% higher and a payback period (criterion C4) that is about 9% longer compared to the alternatives that are similar in relation to STCs but use the M1 insulation system, they achieve significant energy savings for water and space heating (criterion C1) as well as a reduction in CO_2 emissions (criterion C2). Thus, they are favored on the ranking list.

With regard to the integrated solar collectors, it can be concluded that, in addition to the STCs' area (the larger the STC area, the greater the hot water energy production), the tilted angle contributes significantly to the energy production efficiency for water heating. For the STCs installed on the roof of the building, the optimal angle is 45°, while for the facade STC it is 40°.

The alternatives with STCs integrated both on the building roof and façade are better positioned on the ranking list regardless of the insulation measure applied in the building envelope (i.e., the insulation system M1 or M2), indicating that their contribution to higher energy production and CO_2 emission reduction compensates for the augmented investment costs and the longer investment return time.

The results of the sensitivity analysis show that small changes in the relative importance of the criteria do not have a significant impact on the ranking of the alternatives, that is, the ranking order of the alternatives is quite stable. As the significance of criterion C3 (i.e., investment cost) increases, the rank of leading alternatives slowly decreases, while the rank of the other alternatives slowly rises.

For preference values above 70 percent (strong dominance) of criterion C3, the order changes and alternatives with lower investment costs become more suitable options.

In general, it may be concluded that the presented AHP model, with respect to other proposed models for the renewable energy renovation of residential building envelopes, has the capacity to break down a complex problem into simpler parts and solve them successively, allowing for a simple and clear calculation procedure.

In addition, the proposed model allows for significant flexibility in modeling decision maker's preference structure of criteria weights, with the possibility to divide them into several levels of sub-criteria. This allows the 2030 key targets to be incorporated directly into the model as sub-criteria, enabling a direct evaluation of alternatives in relation to them, and thus a more precise selection of the best one.

Finally, the model's capacity to incorporate both qualitative and quantitative criteria that might have different units and scales without the need to transform them into the same unit contributes to its simplicity of use.

The main limitations of the proposed model are (a) the subjective nature of the AHP method, i.e., the dependence on human judgment (expert opinions) for pairwise comparison of alternatives/criteria; (b) consistency issues related to judgment in the AHP, especially in the case of a large number of alternatives/criteria; and (c) high computational requirements, including the time spent for expert evaluations (for pairwise comparison of alternatives and criteria) in the case of a large number of alternatives/criteria. These issues may be the subject of further research, while considering that in practice there are criteria that require subjective evaluation (e.g., aesthetics, well-being, satisfaction, and happiness).

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