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*Case Report*

# Application of the Hybrid MCDM Method for Energy Modernisation of an Existing Public Building—A Case Study

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**Abstract:** The existing public utility building belonging to the Forest Experimental Station of the Poznań University of Life Sciences, due to high energy consumption and related costs, has qualified for deep energy modernisation or consideration for the construction of a new building. One of the goals is to achieve carbon neutrality and have a positive energy balance. The article uses the hybrid DEMATEL-AHP/ANP-VIKOR method. The methodology used is distinguished by the creation of a set of decision-making criteria and the identification of the relationship between them, which is determined by conducting a survey of a group of experts using the Delphi method, as well as determining the preferences of the decision-maker using a survey of the target group using social research. Two different models of the decision-maker's preferences have been developed, taking into account the selected decision criteria, and four acceptable technical solutions have been identified. As a result of the calculations performed, a ranking of the solutions has been developed, from the most preferred to the least accepted. Variant 3B has been identified as the best solution with respect to eight evaluation criteria for both of the adopted models of the decision-maker's preferences. The ranking index $R_i$ coefficient for this variant ranged between 0.733 and 0.901, while for the other variants, it was lower and amounted to between 0.106 and 0.274 for variant 1, 0.166 and 0.290 for variant 2 and 0.403 and 0.437 for variant 3A. The methodology used for the case study has proved to be applicable. The presented methodology can be used to design new buildings (not only residential) with almost zero energy consumption, as well as those with a positive energy balance, and can also be used for deep energy modernisation. In this article, it was applied for the first time to the energy modernisation of an existing public building.

**Keywords:** plus-energy buildings; planning methodology; multi-criteria analysis



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## 1. Introduction

The growing awareness of the consequences of decisions made and the great importance of many of them has undoubtedly contributed to the development of multiple criteria decision-making (MCDM) methods, creating the field of operations research. MCDM methods are used to evaluate and construct a ranking of decision variants, which are usually elements of a set of acceptable solutions. There have been many proposals for the analysis and synthesis of complex decision-making problems, among which the following works deserve special attention [1–4]. The large number of methods make it difficult to choose the best one. The final decision is influenced by many factors, including the nature of the issue under consideration, the possibilities offered by each method, the construction or use of the existing tool and its perception, flexibility, speed and ease of use. However, there are universal solutions, the usefulness of which has been tested using many practical examples, particularly those related to construction, obtaining the desired and satisfactory results. The work [5] uses fuzzy set theory, which can play a significant role in a decision-making situation in the construction industry. Fuzzy MCDM was used to categorise alternative buildings by their overall energy performance. The aim of the work [6] was to prioritise the important factors influencing the energy efficiency of a building. To obtain the results, fuzzy set theory and the DEMATEL method were used. During the work [7], the economic, environmental and energy efficiency of the CCHP microgrid system was assessed using a hybrid approach, which included the grey-DEMATEL, TOPSIS and DQGRA methods. Compared to the four other MCDM models, the proposed hybrid MCDM model is highly suitable and effective in assessing system performance, but a targeted adjustment is required. The work [8] shows the application potential of the DEMATEL method in identifying the role of the factors influencing the quality of the indoor climate in passive buildings. The method used was a simple, but reliable and advantageous, tool that enabled the decomposition and then selection of the most important parameters shaping the comfort of the climate, as well as indicating the relationships between them. In turn, the work [9] presents an analysis of the selection of a method for supplying electricity to a public building with a photovoltaic (PV) array using the analytic hierarchy process and analytic network process (AHP/ANP) methods, in which the main decision criteria were technical, economic, energy and environmental. The results of the analyses have shown the benefits of using energy obtained from solar radiation conversion as an interesting supplement to the conventional energy balance of a public utility building.

In paper [10], a combination of the DEMATEL, ANP and VIKOR methods for low-emission building planning was proposed. The hybrid method proved successful. The proposed method will be applied in other fields, such as green evaluation and energy saving assessments. Hybrid MCDM methods are also used to support decisions on the selection of renewable energy sources with positive effect [11–17].

The development of MCDM methods is progressing rapidly all the time. Many researchers around the world are improving or creating new multi-criteria methods. The main arguments for their development are the ambiguities that often occur due to the lack of complete information and the ambiguities resulting from the qualitative assessment of decision-makers, which can lead to subjective opinions. One of the alternatives is to introduce a team of experts—as in the methodology proposed in this article. New fuzzy methods have been proposed for classical MCDM methods, including fuzzy TOPSIS, fuzzy VIKOR, fuzzy AHP and so on. Compared to classic MCDM, the new methods can better deal with issues characterised by vagueness and ambiguity. However, in the face of the complexity and volatility of real-world decision problems, new MCDM methods are still needed to better make decisions on practical issues. The methodology used in this article is distinguished by the creation of a set of decision-making criteria and the identification of the relationship between them, which is determined by conducting a survey of a group of experts using the Delphi method, as well as determining the preferences of the decision-maker using a survey of the target group using social research. These two functions mean that it can compete with other MCDM methods, including fuzzy ones [18–27].

The use of renewable energy sources is also associated with the possibility of its storage. As many alternatives exist, selecting the appropriate technology becomes a key challenge. The following articles use the TOPSIS method for this purpose [28–32].

Low-emission energy planning can lead to independence from fossil fuels and reduce carbon dioxide emissions into the atmosphere. At present, it has become a necessity to reduce energy consumption by improving energy efficiency. The construction industry consumes almost 40% of the total energy in the world, which, moreover, comes from non-renewable energy sources and contributes to greenhouse gas emissions [33–37]. It is a huge energy resource that can be reduced by improving the energy performance of individual facilities, leading to carbon neutrality and the creation of buildings with a positive energy balance [38–43]. The concept of a smart city is assumed to use resources more efficiently and in an innovative, creative and intelligent manner. The work [44] presents analyses of the factors characterizing smart sustainable buildings and the possibilities for their development.

This article presents a multi-criteria analysis of the choice for the Forest Experimental Station headquarters using the author's methodology for designing residential buildings with a positive energy balance, which is based on a hybrid approach that includes the DEMATEL-AHP/ANP-VIKOR methods. The methodology has been described in the work [45] and was subsequently used for the first time in the publication [46]. Due to the fact that the methodology proved to be applicable to newly designed buildings with a positive energy balance, the decision was made to test it for an existing building that will undergo thermal modernisation. This article is the first application of the algorithm in question for the deep energy thermo-modernisation of an existing public building.

## 2. Materials

The Forest Experimental Station in Murowana Goślina is a unit of the Poznań University of Life Sciences. It is a field base for research and teaching in the areas of forestry, the wood industry and related disciplines. The area of the station is currently 4655 ha, including 4106 ha of forest that constitutes the central part of the forest area known as the Zielonka Forest Landscape Park, a large forest complex located closest to Poznań [47].

As the existing headquarters building is ageing, its operating costs are high and it uses no renewable energy sources, the decision has been made to either modernise the existing facility or build a new one. One of the goals of the modernised or new facility is to achieve carbon neutrality and create a building with a positive energy balance, which will emphasise the green character (the heritage and image) of the station.

## 3. Methodology

The author's methodology for designing residential buildings with a positive energy balance (Figure 1) was used to select the most advantageous solution for the new headquarters of the Forest Experimental Station, taking into account two different models of the decision-maker's preferences ('economic preference' and 'social and environmental preference') and the selected decision sub-criteria. Four technical solutions have been identified in line with the principles and guidelines for designing buildings with a positive energy balance. All of the analysed variants of the solutions meet the requirements of the Passive House Standard of the Passive House Institute (PHI) [48–53].

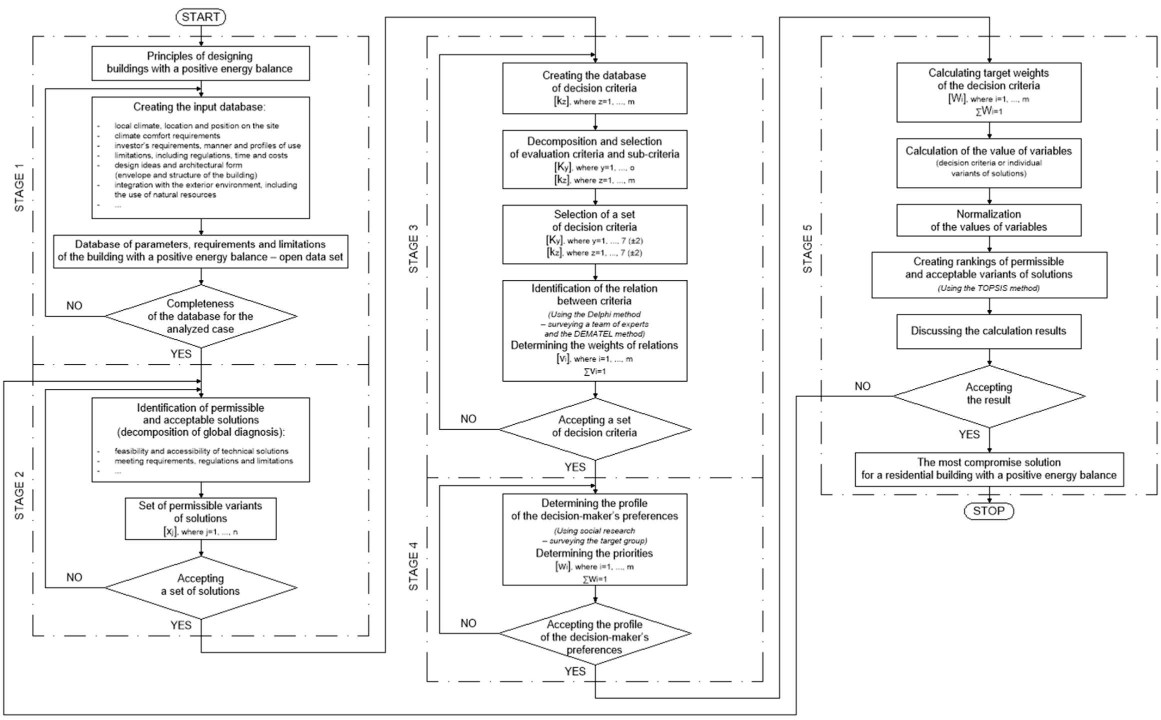


**Figure 1.** Methodology for designing a residential building with a positive energy balance.

### 3.1. STAGE I: Building the Input Database for a Specific Project

Following the guidelines of the Forest Experimental Station, the following input database was adopted for selecting a set of permissible and acceptable solutions:

1. The usable area of the entire building will be approximately 300–400 $m^2$;
2. The building will be designed for 15 employees;
3. There will be office space;
4. There will be a conference room for 20 people and a separate meeting room for 5–6 people;
5. There will be a room with a space for displaying the heritage of the Forest Experimental Station;
6. The building will be modern, but will take into account the green character (the heritage and image) of the station;
7. The building will be fully integrated with the external environment, including through the use of natural resources;
8. The building will be equipped with renewable energy sources and clean technologies;
9. The building will have a positive energy balance and achieve carbon neutrality;
10. Location and climate—the city of Poznań, south-oriented building;
11. Location in a sheltered area—natural shade;
12. Simple architectural and spatial form;
13. Standard method and profile of use of an office building;
14. High requirements for climate comfort—the building will be equipped with active heating, cooling and lighting installations and mechanical supply and exhaust ventilation systems with a highly efficient heat recovery exchanger ($\geq$75%);
15. Restrictions resulting from the Polish regulations, in line with the Regulation of the Minister of Infrastructure and Construction on technical conditions, to be met by the buildings and their location;
16. Building completion time—maximum five years;
17. Maximum investment costs of PLN 3.5 million net;
18. The value range of features (from minimum to maximum) that describe the decision criteria from the set of evaluation criteria and sub-criteria.

The input database was developed following the basic principles of designing residential buildings with a positive energy balance.

### 3.2. STAGE II: Identifying Permissible and Acceptable Solutions for a Residential Building with a Positive Energy Balance

Four technical solutions, which are permissible and acceptable due to the input database and meet the imposed requirements, guidelines and restrictions, have been proposed.

#### 3.2.1. Variant 1

In variant 1, it is proposed to modernise the existing headquarters of the Forest Experimental Station in Murowana Goślina.

The modernisation will involve:

(a) Conducting thermal modernisation of the building envelope in line with the current building regulations (WT2021), including the insulation of external walls with polystyrene of a minimum thickness of 20 cm (thermal conductivity 0.033 W/mK), roof insulation with polystyrene of a minimum thickness of 25 cm (thermal conductivity 0.031 W/mK), replacing windows with those having a UMAX = 1.1 W/$m^2$K coefficient;
(b) Replacing the building’s heat source, which is a wood-burning stove, with an air-to-water heat pump and using a peak heat source in the form of a biomass boiler;
(c) Replacing the existing radiators and heating installation with new ones;
(d) Installing a PV array on the roof of the existing building;
(e) Using energy-saving LED lighting (disassembly/assembly);
(f) Adapting the existing water and sewage systems to the new layout of the building (disassembly/assembly);

(g) Converting the existing, and constructing new, electrical and tele-technical installations adapted to the new layout of the building (disassembly/assembly);
(h) Connecting the sanitary sewage system to the network located on Rogozińska Street;
(i) Adapting the premises (including reconstruction) to the current needs of the users.

#### 3.2.2. Variant 2

In variant 2, it is proposed to use part of the existing Science and Didactic Centre of the Poznań University of Life Sciences, commonly known as the 'Dormitory in Zielonka', which belongs to the Forest Experimental Station, located in Zielonka in the Murowana Goślina commune. It is proposed to develop an area of approximately 300 $m^2$ in the existing accommodation section and modernise it, adapting it to the needs of the current requirements of the investor.

The modernisation will involve:

(a) Adapting the premises (including their reconstruction) to the current needs of the users;
(b) Installing an air-to-water heat pump as a backup heat source for the existing wood-burning solid-fuel stove;
(c) Replacing the existing radiators and heating installation with new ones;
(d) Using energy-saving LED lighting (disassembly/assembly);
(e) Adapting the existing water and sewage systems to the new layout of the building (disassembly/assembly);
(f) Converting the existing, and constructing new, electrical and tele-technical installations, adapted to the new layout of the building (disassembly/assembly);
(g) Installing a PV array on the roof of the existing building;
(h) Using a mechanical ventilation system with heat recovery (85%) and distributing ventilation ducts in the building's attic.

#### 3.2.3. Variant 3

In variant 3, it is proposed to use an available area of plot no. 266/37, amounting to approximately 900 $m^2$, which is the current location of a garage shelter in the south-eastern part of the plot with a total area of approximately 0.294 ha = 2940 $m^2$, for constructing new headquarters for the Forest Experimental Station. Within the available space of the plot in question, it is proposed to build a new headquarters for the Forest Experimental Station according to the following sub-variants:

Variant 3A

This variant proposes the construction of new headquarters for the Forest Experimental Station in line with the classic brick-technology building standard that meets the current regulations (WT2021). The construction of the new headquarters will involve:

(a) Meeting the current regulations on the insulation of partitions and the coefficient of demand for primary energy (WT2021);
(b) Installing a mechanical ventilation system with heat recovery (85%);
(c) Installing an air-to-water heat pump as a source of heating and cooling;
(d) Building water and sewage installations;
(e) Building electrical and tele-technical installations specifically designed for the layout of the building;
(f) Installing a PV array on the roof;
(g) Using energy-saving LED lighting;
(h) Connecting the sanitary sewage system to the network located on Rogozińska Street;
(i) Connecting to the public water supply system;
(j) Creating the number and size of rooms currently required.

Variant 3B

Variant 3B proposes the construction of new headquarters for the Forest Experimental Station in line with the Passive House Standard of the PHI, using cross-laminated timber

(CLT) technology. This standard exceeds the requirements of energy efficiency in Poland and is based on the idea of passive house construction, which combines high operational comfort (fresh air, thermal comfort, acoustic and visual comfort) with very low energy consumption and high satisfaction of users with the surrounding conditions. When designing this type of structure, attention is also paid to other issues, such as water consumption, the use of appropriate building materials, the impact on the environment and the value of the emissions of harmful substances into the atmosphere. The main goal is to reduce the energy consumption, which is only one of many aspects of sustainable development, and the others should also not be forgotten. The new facility will have almost zero energy consumption and its favourable energy characteristics will ensure the provision of primary energy on site only from renewable sources, which directly fits with the characteristics of the Forest Experimental Station.

The demand for energy in the analysed buildings was calculated using the ArCADia-TERMOCAD software by Intersoft [54].

### 3.3. STAGE III: Selecting a Set of Decision Criteria and Identifying the Relationship between the Criteria

The decision criteria for residential buildings with a positive energy balance have been described and selected in the publications [45,46]. To choose the solution for a new headquarters for the Forest Experimental Station, these were defined by the analyst and the decision-maker and are summarised in Table 1.

**Table 1.** Set of selected decision criteria.

| No. | Criterion Group | Parameter Symbol | Criterion | Criterion Symbol | Preference | Value Range |
|---|---|---|---|---|---|---|
| [-] | [-] | [-] | [-] | [-] | [-] | [-] |
| 1 | Technical criteria | $c_T$ | Total building completion time ($T_{BLD}$) | $c_{T\ T,BC,i}$ | decreasing | (0, 1> |
| 2 | | | Difficulties in implementation ($D_{IMP}$) | $c_{T\ D,IMP,i}$ | decreasing | (0, 1> |
| 3 | Energy criteria | $c_{EN}$ | Total primary energy consumption ($PE_{TOTAL}$) | $c_{EN\ PE,TOTAL,i}$ | decreasing | (0, 1> |
| 4 | | | Total generated usable renewable energy ($UE_{RES}$) | $c_{EN\ UE,RES,i}$ | increasing | (0, 1> |
| 5 | Exergy criteria | $c_{EX}$ | Use of natural heating, cooling and lighting strategies ($N_{ST}$) | $c_{EX\ N,ST,i}$ | increasing | (0, 1> |
| 6 | Economic criteria | $c_{EC}$ | Total operational cost (TOC) | $c_{EC\ TOC,i}$ | decreasing | (0, 1> |
| 7 | | | Total prime cost of the investment ($TC_{INV}$) | $c_{EC\ PC,INV,i}$ | decreasing | (0, 1> |
| 8 | Social criteria | $c_S$ | Compliance with air quality parameters (AQ) | $c_{S\ AQ,i}$ | increasing | (0, 1> |
| 9 | | | Impact of the building and its installations on the surrounding environment ($I_{ENV}$) | $c_{S\ I,ENV,i}$ | decreasing | (0, 1> |
| 10 | Environmental criteria | $c_{ENV}$ | Life-cycle analysis of the building (LCA) | $c_{ENV\ LCA,\ i}$ | decreasing | (0, 1> |

Then, the DEMATEL method was used to determine the relationship between the individual evaluation criteria. For this purpose, research was carried out in line with the idea of the Delphi method and described in the work [45]. The author's expert questionnaire was used, which was addressed to experts. The sampling criterion was defined. The respondents were people with knowledge and experience concerning the analysed case.

Then, a direct impact matrix, a normalised direct impact matrix and a total impact matrix were developed (see Supplementary File S1).

Table 2 presents the role and importance of the individual criteria in the context of the overall impact. According to the DEMATEL method, the 's+' ('D+R') and 's−' ('D−R') indices were determined. The causal factors are shown in bold font (s− > 0), while the effect criteria (s− < 0) are in italics. Figure 2 it is the cause-and-effect diagram, in which a hierarchy and correlation between the individual elements are shown.

**Table 2.** The role and importance of individual main evaluation criteria.

| | D+R<br>s+ | D-R<br>s− |
|---|---|---|
| $c_{T\ T,BC,i}$ | **0.61** | **0.59** |
| $c_{T\ D,IMP,i}$ | *0.58* | *−0.04* |
| $c_{EN\ PE,TOTAL,i}$ | *0.94* | *−0.71* |
| $c_{EN\ UE,RES,i}$ | **0.84** | **0.51** |
| $c_{EX\ N,ST,i}$ | **1.19** | **1.19** |
| $c_{EC\ TOC,i}$ | *0.62* | *−0.52* |
| $c_{EC\ PC,INV,i}$ | *0.80* | *−0.48* |
| $c_{S\ AQ,i}$ | **0.36** | **0.22** |
| $c_{S\ I,ENV,i}$ | *0.49* | *−0.37* |
| $c_{ENV\ LCA,\ i}$ | *0.65* | *−0.38* |

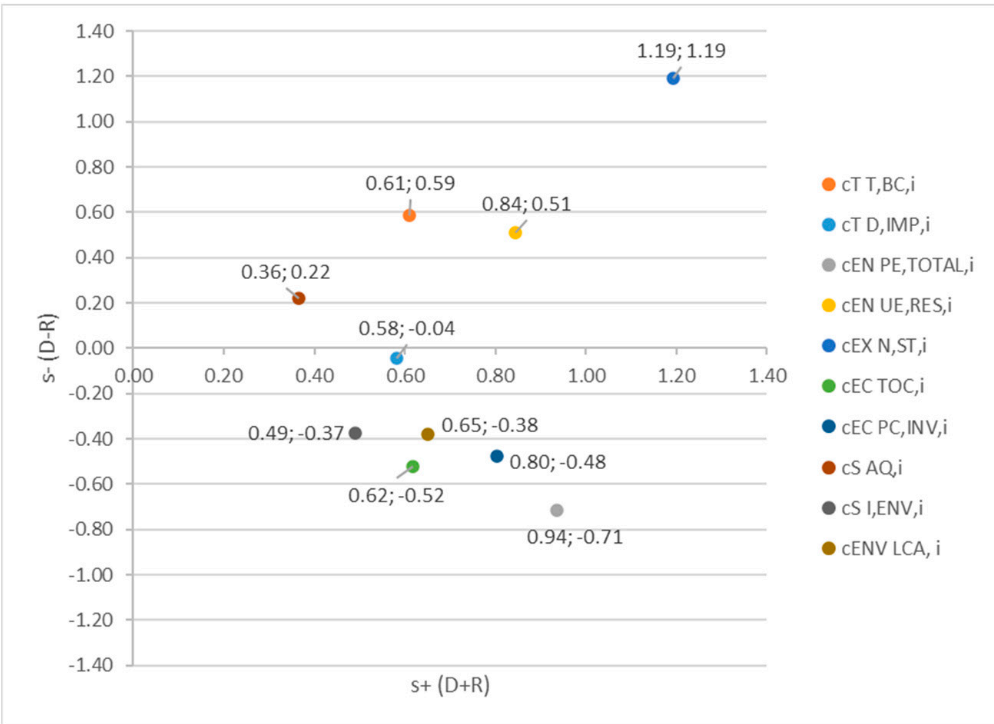


**Figure 2.** Classification of evaluation criteria.

The DEMATEL method was used to determine the weights of the relations between the individual evaluation criteria. Table 3 shows the evaluation criteria, along with the values of the calculated weights of relations. Those weights of relations whose values are over 10% are marked in bold.

After carrying out the analysis using the DEMATEL method, it is possible to precisely characterise the relations that do or do not occur between the individual evaluation criteria. All dependencies between individual evaluation criteria should be taken into account. This method has the advantage of being transparent in reflecting the interrelations between a wide set of elements.

**Table 3.** Selected decision criteria for selecting new headquarters for the Forest Experimental Station with a positive energy balance and the weights of relations.

| No. | Criterion Group | Parameter Symbol | Criterion | Criterion Symbol | Relation Weight $v_j$ |
|---|---|---|---|---|---|
| [-] | [-] | [-] | [-] | [-] | [-] |
| 1 | Technical criterion | $c_T$ | Total building completion time ($T_{BLD}$) | $c_{T\ T,BC,i}$ | **0.124** |
| 2 | | | Difficulties in implementation ($D_{IMP}$) | $c_{T\ D,IMP,i}$ | 0.078 |
| 3 | Energy criterion | $c_{EN}$ | Total primary energy consumption ($PE_{TOTAL}$) | $c_{EN\ PE,TOTAL,i}$ | 0.087 |
| 4 | | | Total generated usable renewable energy ($UE_{RES}$) | $c_{EN\ UE,RES,i}$ | **0.154** |
| 5 | Exergy criterion | $c_{EX}$ | Use of natural heating, cooling and lighting strategies ($N_{ST}$) | $c_{EX\ N,ST,i}$ | **0.253** |
| 6 | Economic criterion | $c_{EC}$ | Total operational cost (TOC) | $c_{EC\ TOC,i}$ | 0.051 |
| 7 | | | Total prime cost of the investment ($TC_{INV}$) | $c_{EC\ PC,INV,i}$ | 0.083 |
| 8 | Social criterion | $c_S$ | Compliance with the air quality parameters (AQ) | $c_{S\ AQ,i}$ | 0.062 |
| 9 | | | Impact of the building and its installations on the surrounding environment ($I_{ENV}$) | $c_{S\ I,ENV,i}$ | 0.042 |
| 10 | Environmental criteria | $c_{ENV}$ | Live-cycle analysis of the building (LCA) | $c_{ENV\ LCA,\ i}$ | 0.066 |
| | | | | **total** | **1.000** |

The most important evaluation criteria are those that have a strong cause character as they have the greatest impact on the other evaluation criteria. Above all, one should focus on these to achieve the highest possible value.

The tool—that is, the DEMATEL method—has fulfilled the expected function and made it possible to identify relations between the evaluation criteria. The set of decision criteria and the values of their relations have been approved by the analyst and the decision-maker. The results obtained with this research method will be used in the next stage of the methodology's application as the weights of the relations.

### *3.4. STAGE IV: Determining the Profile of the Decision-Maker's Preferences*

The next step was to define the profile of the decision-maker's preferences. It was developed using a target group survey, a method applied in social research, which has been described in the work [45]. In the analysed case, it was decided to adopt two preference profiles of the decision-maker: 'Economic preference' and 'socio-environmental preference', which were established by the analyst and the decision-maker. To compare the pairwise elements in line with the AHP/ANP methods, a discrete and non-negative evaluation was made using Saaty's nine-point scale. It shows the degree of advantage (dominance/preference scale) of one evaluation criterion over another, including point '1', indicating no advantage. For the collected data, the geometric consistency index (GCI) was calculated, which meets the necessary condition of GCI > GCIperm. In line with the above, the collected evaluations are highly reliable and accurate. Supplementary File S2 lists the evaluation criteria comparison matrices. For the analysed preference models, Table 4 and Figure 3 present the weights for the evaluation criteria, which were calculated using the AHP/ANP methods. After determining the weight vectors for the selected evaluation criteria, these can be classified from the most preferred (those having a high value) to the least significant (those having a low value). In Table 4, the preference weights whose values are over 10% are marked in bold.

**Table 4.** Weight vectors for the selected evaluation criteria: 'Economic preference' and 'social and environmental preference'.

| | | | Economic Preference | Social and Environmental Preference |
|---|---|---|---|---|
| **No.** | **Criterion** | **Criterion Symbol** | **Normalized Value** | **Normalized Value** |
| [-] | [-] | [-] | [-] | [-] |
| 1 | Total building completion time ($T_{BLD}$) | $c_{T\ T,BC,i}$ | **0.118** | 0.055 |
| 2 | Difficulties in implementation ($D_{IMP}$) | $c_{T\ D.IMP.i}$ | **0.118** | 0.055 |
| 3 | Total primary energy consumption ($PE_{TOTAL}$) | $c_{EN\ PE.TOTAL.i}$ | 0.038 | **0.105** |
| 4 | Total generated usable renewable energy ($UE_{RES}$) | $c_{EN\ UE.RES.i}$ | 0.038 | **0.105** |
| 5 | Use of natural heating. cooling and lighting strategies ($N_{ST}$) | $c_{EX\ N.ST.i}$ | 0.038 | 0.055 |
| 6 | Total operational cost (TOC) | $c_{EC\ TOC.i}$ | **0.231** | 0.055 |
| 7 | Total prime cost of the investment ($TC_{INV}$) | $c_{EC\ PC.INV.i}$ | **0.266** | 0.055 |
| 8 | Compliance with the air quality parameters (AQ) | $c_{S\ AQ.i}$ | 0.054 | **0.171** |
| 9 | Impact of the building and its installations on the surrounding environment ($I_{ENV}$) | $c_{S\ I.ENV.i}$ | 0.054 | **0.290** |
| 10 | Lice-cycle analysis of the building (LCA) | $c_{ENV\ LCA.\ i}$ | 0.044 | 0.055 |
| | | **total** | **1.000** | **1.000** |

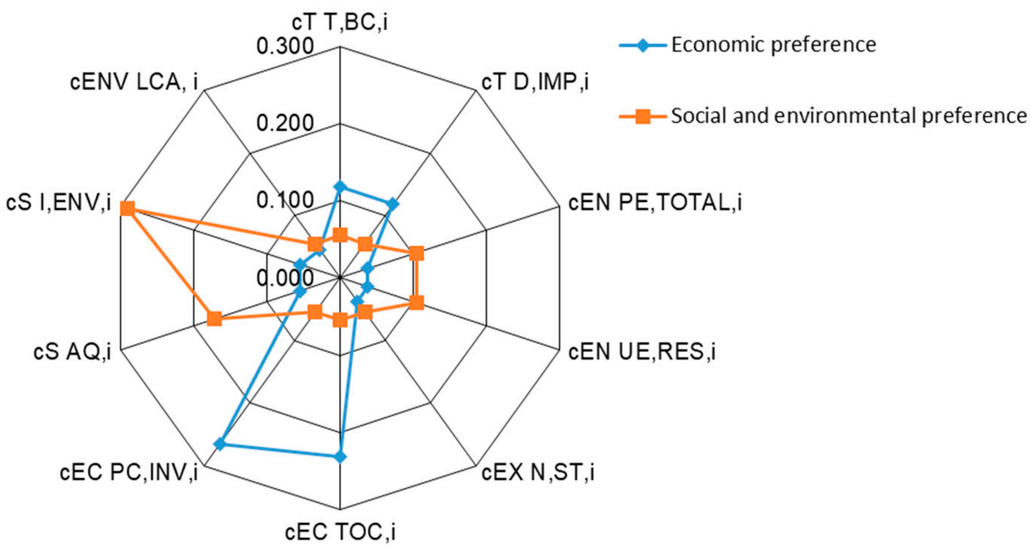


**Figure 3.** Comparison of the preference weights for the evaluation criteria.

The tool, in the form of the AHP/ANP methods, has fulfilled the expected function and made it possible to determine the preference weights for the evaluation criteria depending on the model of the decision-maker's preferences. It is time to go to the fifth stage of the methodology's application.

### 3.5. STAGE V: Choosing a Compromise Solution

The fifth, and final, stage of the applied methodology starts with the calculation of the target weights of the decision criteria, which are developed based on the calculated weights of the relations and priority weights for both of the decision-maker's preference models. Table 5 lists the target preference weights for the evaluation criteria for the 'economic preference' and 'socio-environmental preference' groups of the decision-maker's preferences.

**Table 5.** Target weights for evaluation criteria by 'economic preference' and 'socio-environmental preference'.

| **No.** | **Criterion Group** | **Parameter Symbol** | **Criterion** | **Criterion Symbol** | **Target Weight** $W^{EC}_j$ | $W^{S\text{-}ENV}_j$ |
|---|---|---|---|---|---|---|
| **[-]** | **[-]** | **[-]** | **[-]** | **[-]** | **[-]** | **[-]** |
| 1 | Technical criterion | $c_T$ | Total building completion time ($T_{BLD}$) | $c_{T\ T,BC,i}$ | 0.171 | 0.116 |
| 2 | | | Difficulties in implementation ($D_{IMP}$) | $c_{T\ D,IMP,i}$ | 0.108 | 0.040 |
| 3 | Energy criterion | $c_{EN}$ | Total primary energy consumption ($PE_{TOTAL}$) | $c_{EN\ PE,TOTAL,i}$ | 0.039 | 0.056 |
| 4 | | | Total generated usable renewable energy ($UE_{RES}$) | $c_{EN\ UE,RES,i}$ | 0.070 | 0.252 |
| 5 | Exergy criterion | $c_{EX}$ | Use of natural heating, cooling and lighting strategies ($N_{ST}$) | $c_{EX\ N,ST,i}$ | 0.114 | 0.258 |
| 6 | Economic criterion | $c_{EC}$ | Total operational cost (TOC) | $c_{EC\ TOC,i}$ | 0.139 | 0.037 |
| 7 | | | Total prime cost of the investment ($TC_{INV}$) | $c_{EC\ PC,INV,i}$ | 0.259 | 0.139 |
| 8 | Social criterion | $c_S$ | Compliance with the air quality parameters (AQ) | $c_{S\ AQ,i}$ | 0.039 | 0.039 |
| 9 | | | Impact of the building and its installations on the surrounding environment ($I_{ENV}$) | $c_{S\ I,ENV,i}$ | 0.027 | 0.011 |
| 10 | Environmental criteria | $c_{ENV}$ | Lice-cycle analysis of the building (LCA) | $c_{ENV\ LCA,\ i}$ | 0.034 | 0.052 |
| | | | | **total** | **1.000** | **1.000** |

Then, the direction of preferences should be determined for each evaluation criterion and the values of the variables characterising the four selected variants of the solutions should be calculated. This creates a decision matrix, which is used in the TOPSIS method. The data and results are summarised in Supplementary File S3, while Table 6 presents the numerical values of the calculated indicators, including the preferences for the adopted evaluation criteria.

**Table 6.** Numerical values of indicators and their preferences for the adopted evaluation criteria.

| No. | Criterion Group | Criterion Symbol | Preference | Variant 1 | Variant 2 | Variant 3A | Variant 3B | Unit |
|---|---|---|---|---|---|---|---|---|
| [-] | [-] | [-] | [-] | [-] | [-] | [-] | [-] | [-] |
| 1<br>2 | Technical criterion | $c_{T\ T,BC,i}$<br>$c_{T\ D,IMP,i}$ | decreasing<br>decreasing | 2.50<br>7.00 | 3.50<br>9.00 | 3.00<br>3.00 | 3.00<br>3.00 | yers<br>pts |
| 3<br>4 | Energy criterion | $c_{EN\ PE,TOTAL,i}$<br>$c_{EN\ UE,RES,i}$ | decreasing<br>increasing | 208.21<br>94.27 | 211.25<br>91.93 | 202.05<br>100.44 | 118.99<br>102.38 | kWh/(m$^2$ year)<br>kWh/(m$^2$ year) |
| 5 | Exergy criterion | $c_{EX\ N,ST,i}$ | increasing | 2.00 | 3.00 | 5.00 | 9.00 | pts |
| 6<br>7 | Economic criterion | $c_{EC\ TOC,i}$<br>$c_{EC\ PC,INV,i}$ | decreasing<br>decreasing | 25,619.00<br>2,562,750.00 | 20,229.00<br>2,603,000.00 | 17,860.00<br>3,003,550.00 | 8666.00<br>3,140,300.00 | PLN/year<br>PLN |
| 8<br>9 | Social criterion | $c_{S\ AQ,i}$<br>$c_{S\ I,ENV,i}$ | increasing<br>decreasing | 4.00<br>9.00 | 5.00<br>8.00 | 8.00<br>5.00 | 10.00<br>2.00 | pts<br>pts |
| 10 | Environmental criteria | $c_{ENV\ LCA,\ i}$ | decreasing | 9.00 | 7.00 | 5.00 | 2.00 | pts |

Table 7 lists the maximum permissible numerical values of the indicators, along with the direction of preferences of a given value.

**Table 7.** Permissible numerical values of indicators for the adopted evaluation criteria.

| No. | Criterion Group | Criterion Symbol | Preference | Max | Min | Unit |
|---|---|---|---|---|---|---|
| [-] | [-] | [-] | [-] | [-] | [-] | [-] |
| 1<br>2 | Technical criterion | $c_{T\ T,BC,i}$<br>$c_{T\ D,IMP,i}$ | decreasing<br>decreasing | 3,5<br>10.00 | 0.50<br>1.00 | -<br>- |
| 3<br>4 | Energy criterion | $c_{EN\ PE,TOTAL,i}$<br>$c_{EN\ UE,RES,i}$ | decreasing<br>increasing | 250.00<br>150.00 | 10.00<br>10.00 | -<br>- |
| 5 | Exergy criterion | $c_{EX\ N,ST,i}$ | increasing | 10.00 | 1.00 | - |
| 6<br>7 | Economic criterion | $c_{EC\ TOC,i}$<br>$c_{EC\ PC,INV,i}$ | decreasing<br>decreasing | 30,000.00<br>3,500,000.00 | 5000.00<br>2,000,000.00 | -<br>- |
| 8<br>9 | Social criterion | $c_{S\ AQ,i}$<br>$c_{S\ I,ENV,i}$ | increasing<br>decreasing | 10.00<br>10.00 | 1.00<br>1.00 | -<br>- |
| 10 | Environmental criteria | $c_{ENV\ LCA,\ i}$ | decreasing | 10.00 | 1.00 | - |

The results of the numerical values of the indicators obtained (see Table 7) are then normalised, which is the second stage of the TOPSIS method's application. After normalisation, all indicators are stimulants with values ranging between 0.00 and 1.00 (see Table 8).

The next stage of the TOPSIS method's application involves multiplying the values obtained after normalisation by the target weights of the evaluation criteria (see Table 6) to obtain the adjusted scores. All adjusted calculations are stimulants; therefore, the ideal solution for each of the evaluation criteria is the variant with the maximum value of the adjusted score. On the other hand, the anti-ideal solution is the variant with the minimum value. The adjusted scores and ideal/anti-ideal solutions for both groups of the decision-maker's preferences are shown in Tables 9 and 10.

To create the final ranking of the variants, it is necessary to calculate the distance of each variant from the ideal and anti-ideal solutions in the last stage of the method's application.

After this calculation, the indicator of similarity to the ideal solution is calculated. The distances and ranking factors are summarised in Table 11.

Table 12 presents the final ranking of the analyzed four variants together with numerical values. The same ranking is presented graphically in Figure 4.

**Table 8.** Normalised values of indicators for selected evaluation sub-criteria.

| No. | Criterion Group | Criterion Symbol | Preference | Variant 1 | Variant 2 | Variant 3A | Variant 3B | Unit |
|---|---|---|---|---|---|---|---|---|
| [-] | [-] | [-] | [-] | [-] | [-] | | [-] | [-] |
| 1<br>2 | Technical criterion | $c_{T\ T,BC,i}$<br>$c_{T\ D,IMP,i}$ | decreasing<br>decreasing | 0.20<br>0.14 | 0.14<br>0.11 | 0.17<br>0.33 | 0.17<br>0.33 | -<br>- |
| 3<br>4 | Energy criterion | $c_{EN\ PE,TOTAL,i}$<br>$c_{EN\ UE,RES,i}$ | decreasing<br>increasing | 0.05<br>0.63 | 0.05<br>0.61 | 0.05<br>0.67 | 0.08<br>0.68 | -<br>- |
| 5 | Exergy criterion | $c_{EX\ N,ST,i}$ | increasing | 0.20 | 0.30 | 0.50 | 0.90 | - |
| 6<br>7 | Economic criterion | $c_{EC\ TOC,i}$<br>$c_{EC\ PC,INV,i}$ | decreasing<br>decreasing | 0.20<br>0.78 | 0.25<br>0.77 | 0.28<br>0.67 | 0.58<br>0.64 | -<br>- |
| 8<br>9 | Social criterion | $c_{S\ AQ,i}$<br>$c_{S\ I,ENV,i}$ | increasing<br>decreasing | 0.40<br>0.11 | 0.50<br>0.13 | 0.80<br>0.20 | 1.00<br>0.50 | -<br>- |
| 10 | Environmental criteria | $c_{ENV\ LCA,\ i}$ | decreasing | 0.11 | 0.14 | 0.20 | 0.50 | - |

**Table 9.** Adjusted scores in the evaluation criteria for individual variants: The 'economic preference' group.

| No. | Criterion Group | Criterion Symbol | Adjusted Evaluations—Economic Preference | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Variant 1 | Variant 2 | Variant 3A | Variant 3B | Unit | Positive Ideal | Negative Ideal |
| [-] | [-] | [-] | [-] | [-] | [-] | [-] | [-] | [-] | [-] |
| 1<br>2 | Technical criterion | $c_{T\ T,BC,i}$<br>$c_{T\ D,IMP,i}$ | **0.034**<br>0.015 | 0.024<br>0.012 | 0.028<br>**0.036** | 0.028<br>**0.036** | -<br>- | 0.034<br>0.036 | 0.024<br>0.012 |
| 3<br>4 | Energy criterion | $c_{EN\ PE,TOTAL,i}$<br>$c_{EN\ UE,RES,i}$ | 0.002<br>0.044 | 0.002<br>0.043 | 0.002<br>0.047 | **0.003**<br>**0.048** | -<br>- | 0.003<br>0.048 | 0.002<br>0.043 |
| 5 | Exergy criterion | $c_{EX\ N,ST,i}$ | 0.023 | 0.034 | 0.057 | **0.103** | - | 0.103 | 0.023 |
| 6<br>7 | Economic criterion | $c_{EC\ TOC,i}$<br>$c_{EC\ PC,INV,i}$ | 0.027<br>**0.202** | 0.034<br>0.199 | 0.039<br>0.172 | **0.080**<br>0.165 | -<br>- | 0.080<br>0.202 | 0.027<br>0.165 |
| 8<br>9 | Social criterion | $c_{S\ AQ,i}$<br>$c_{S\ I,ENV,i}$ | 0.016<br>0.003 | 0.020<br>0.003 | 0.032<br>0.005 | **0.039**<br>**0.013** | -<br>- | 0.039<br>0.013 | 0.016<br>0.003 |
| 10 | Environmental criteria | $c_{ENV\ LCA,\ i}$ | 0.004 | 0.005 | 0.007 | **0.017** | - | 0.017 | 0.004 |
| | | **total** | 0.370 | 0.376 | 0.425 | **0.533** | | **0.576** | **0.318** |

**Table 10.** Adjusted scores in the evaluation criteria for individual variants: The 'social and environmental preference' group.

| No. | Criterion Group | Criterion Symbol | Adjusted Evaluations—Social and Environmental Preference | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Variant 1 | Variant 2 | Variant 3A | Variant 3B | Unit | Positive Ideal | Negative Ideal |
| [-] | [-] | [-] | [-] | [-] | [-] | [-] | [-] | [-] | [-] |
| 1 | Technical criterion | $c_{T\ T,BC,i}$ | **0.023** | 0.017 | 0.019 | 0.019 | - | 0.023 | 0.017 |
| 2 | | $c_{T\ D,IMP,i}$ | 0.006 | 0.004 | **0.013** | **0.013** | - | 0.013 | 0.004 |
| 3 | Energy criterion | $c_{EN\ PE,TOTAL,i}$ | 0.003 | 0.003 | 0.003 | **0.005** | - | 0.005 | 0.003 |
| 4 | | $c_{EN\ UE,RES,i}$ | 0.158 | 0.155 | 0.169 | **0.172** | - | 0.172 | 0.155 |
| 5 | Exergy criterion | $c_{EX\ N,ST,i}$ | 0.052 | 0.078 | 0.129 | **0.233** | - | 0.233 | 0.052 |
| 6 | Economic criterion | $c_{EC\ TOC,i}$ | 0.007 | 0.009 | 0.010 | **0.021** | - | 0.021 | 0.007 |
| 7 | | $c_{EC\ PC,INV,i}$ | **0.109** | 0.107 | 0.093 | 0.089 | - | 0.109 | 0.089 |
| 8 | Social criterion | $c_{S\ AQ,i}$ | 0.016 | 0.020 | 0.031 | **0.039** | - | 0.039 | 0.016 |
| 9 | | $c_{S\ I,ENV,i}$ | 0.001 | 0.001 | 0.002 | **0.005** | - | 0.005 | 0.001 |
| 10 | Environmental criteria | $c_{ENV\ LCA,\ i}$ | 0.006 | 0.007 | 0.010 | **0.026** | - | 0.026 | 0.006 |
| | | **total** | 0.380 | 0.400 | 0.480 | **0.622** | | **0.646** | **0.348** |

**Table 11.** Ideal and anti-ideal solutions, distances and ranking factors.

| Economic Preference | | | | | | |
|---|---|---|---|---|---|---|
| No. | Variant | Positive-Ideal Solution | Negative-Ideal Solution | Distance $d_i^+$ | Distance $d_i^-$ | Ranking Index Ri |
| 1 | Variant 1 | 0.576 | 0.318 | 0.102 | 0.039 | 0.274 |
| 2 | Variant 2 | | | 0.090 | 0.037 | 0.290 |
| 3 | Variant 3A | | | 0.070 | 0.047 | 0.402 |
| **4** | **Variant 3B** | | | **0.038** | **0.103** | **0.733** |
| **Social and Environmental Preference** | | | | | | |
| No. | Variant | Positive-ideal Solution | Negative-Ideal Solution | Distance $d_i^+$ | Distance $d_i^-$ | Ranking Index Ri |
| 1 | Variant 1 | 0.646 | 0.348 | 0.185 | 0.021 | 0.104 |
| 2 | Variant 2 | | | 0.159 | 0.032 | 0.167 |
| 3 | Variant 3A | | | 0.107 | 0.081 | 0.432 |
| **4** | **Variant 3B** | | | **0.020** | **0.185** | **0.901** |

**Table 12.** Final ranking of variants.

| Lp. | Variant | Ranking Index Ri | |
|---|---|---|---|
| | | Economic Preference | Social and Environmental Preference |
| [-] | [-] | [-] | [-] |
| **1** | **Variant 3B** | **0.733** | **0.901** |
| 2 | Variant 3A | 0.402 | 0.432 |
| 3 | Variant 2 | 0.290 | 0.167 |
| 4 | Variant 1 | 0.274 | 0.104 |

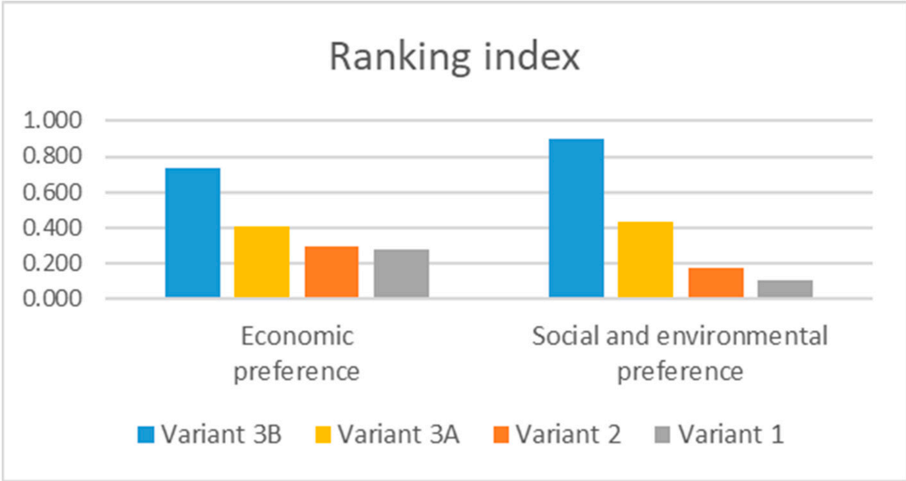


**Figure 4.** Final ranking of variants.

Table 13 presents the normalised final ranking of the analyzed four variants along with numerical values. The same ranking is presented graphically in Figure 5.

**Table 13.** Final ranking of variants—normalised.

| Lp. | Variant | Ranking Index—Normalised | |
|---|---|---|---|
| | | Economic Preference | Social and Environmental Preference |
| [-] | [-] | [-] | [-] |
| **1** | **Variant 3B** | **1.000** | **1.000** |
| 2 | Variant 3A | 0.549 | 0.480 |
| 3 | Variant 2 | 0.396 | 0.186 |
| 3 | Variant 1 | 0.374 | 0.116 |

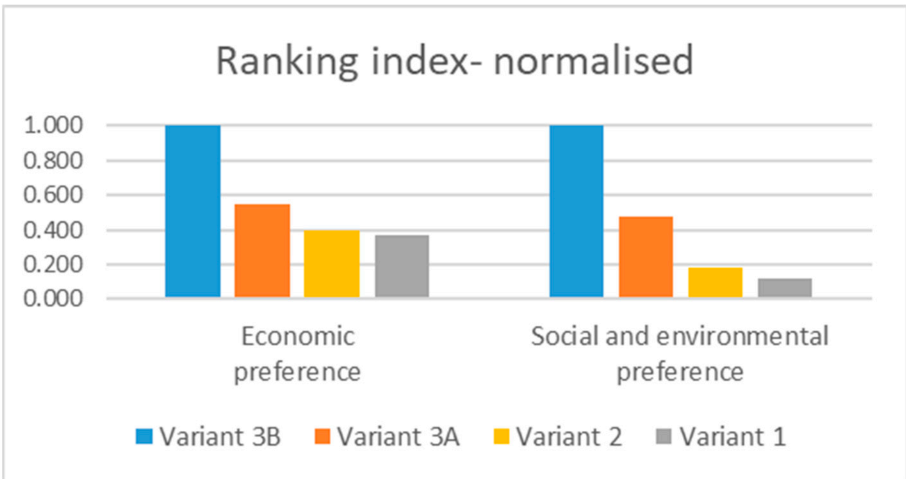


**Figure 5.** Final ranking of variants—normalised.

## 4. Discussion

The best compromise solution regarding the modernisation of the existing headquarters or the construction of a new one is the construction of a new headquarters in line with variant 3B; that is, a building constructed in line with the Passive House Standard using CLT technology. The same result was obtained for both groups of the decision-maker's preferences with the differences in the values between the individual groups caused by their different preferences. The $R_i$ ranking coefficient for this variant ranged between 0.733

and 0.901, while for the other variants, it was lower and amounted to between 0.106 and 0.274 for variant 1, 0.166 and 0.290 for variant 2 and 0.403 and 0.437 for variant 3A.

The construction of a new building that meets only the current regulations on energy efficiency is a worse solution, while both variants involving the modernisation of the existing buildings are by far the worst solutions from the point of view of the multi-criteria analysis carried out, and are at a similar, very low level of the evaluation value.

In a significant number of the decision criteria, variant 3B is the ideal solution, in accordance with the TOPSIS method; that is, with regard to eight of the ten possible evaluation criteria for both models of preferences. This variant is by far the best in many of the evaluation criteria, notably: the use of natural heating, cooling and lighting strategies (NST); total operational cost (TOC); compliance with the air quality parameters (AQ); the impact of the building and its installations on the surrounding environment ($I_{ENV}$); and the life-cycle analysis of the building (LCA). The compromise solution proved to be the farthest from the ideal solution in one evaluation criterion; that is, the total prime cost of the investment ($TC_{INV}$).

## 5. Conclusions

The methodology used for this case study has proved to be applicable. The developed methodology facilitates the process of designing buildings (not only residential) with almost zero energy consumption, as well as those with a positive energy balance.

It is observed that the construction sector tends to reduce primary energy consumption, increase the efficiency of energy conversion in the solutions implemented for a building's technical equipment and use renewable energy sources in line with the idea of sustainable development. At present, both newly designed and modernised buildings must meet the regulations in force in a given country, which are modified to improve energy efficiency, leading to a reduction in energy consumption in the built environment, thus achieving carbon neutrality. The decision criteria should be properly selected and evaluated in the initial phase of any construction investment.

The methodology proposed in this article can be used to select a compromise solution for the modernisation of existing buildings to the standard of buildings with a positive energy balance. The choice of decision criteria can be adjusted to the specific profile of a decision-maker's preferences, given the differences in the perception of certain regularities occurring for different populations at the level of a province, country or continent and/or for different target groups, including commercial investors, public investors, designers, ecologists, future users and, more generally, all those who influence the choice of a compromise solution in construction.

The applicability of the presented methodology is intended to be extended to other types of buildings. Further case study analyses are planned, including deeply modernised historic buildings and sacral buildings. The set of decision-making criteria may change, and they should be adapted each time to the subject of the analysis. The method of evaluating individual point-based decision criteria may change so that they are not dependent on the expert making the assessment, enabling the possible implementation of a team of experts or social research.

In an independent article, the methodology proposed in this paper will be compared with other currently used methodologies, including new generation methods or fuzzy methods. It is possible that the proposed methodology will be improved in the future.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16083475/s1, Supplementary File S1: Direct-relation matrix, normalised direct-relation matrix and total-relation matrix; Supplementary File S2: Questionnaire of the decision-maker's preferences—Pairwise comparison matrices; Supplementary File S3: Calculation of the values of variables, i.e., the values of decision criteria for individual variants of permissible solutions for buildings.

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