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Selection of floor heating systems with use of multi-criteria decision analysis method

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Abstract: Using Multiple-criteria Decision Analysis (MCDA), the most favourable floor heating system of a detached house has been selected. The analysis also includes an assessment of the performance of this type of heating on small surfaces (up to 20 m^2). The choice was made among eight heating variants, adopting various systems available on the construction market powered by water or electricity, including traditional with „wet" screeds, „dry" screeds and lightweight floor heating systems without floor screeds. From the set of 14 evaluation criteria, the eight most important ones were identified. Using the summed corrected indicator of mathematical analysis, it was assessed that the best variant is a lightweight floor water heating system on a reactive adhesive without screeds with aluminium foil.

Keywords: MCDA, lightweight underfloor heating, set of criteria, radiant floor heating

1. Introduction

Every day, people face choices with regards to more or less significant matters. This also applies to topics that arise during the construction of a house. One of them is the choice of a heating system. In recent years, underfloor heating has become increasingly popular, and therefore the purpose of the article is to choose the best of the eight variants selected. The basis for this was the important criteria described here that characterize this surface heating system. The reason for this is that it has many advantages, including the most important one, a high thermal efficiency at a low supply temperature, good cooperation with devices using renewable energy sources and the provision of thermal comfort, especially the so-called „comfort of warm feet", where the temperature distribution is close to the ideal one for a human being. To make the right decision, it is necessary to choose the possible options for solutions to the topic we are interested in and define the evaluation criteria. Based on many criteria, we determine the final set and analytically choose the best variant. MCDA according to [1] allows you to determine which variant satisfies the investor's requirements to the highest degree and this decision is determined as optimal. An optimisation is particularly important when the effects of decisions have a long-term impact not only on the future life of the person choosing but for future generations. In this article, Multiple-criteria Decision Analysis was carried out based on the work [1-3]. It is worth noting that there are other current positions in the literature that deals with the development of MCDA methods towards application as multi-attribute utility theory (e.g. AHP- example in [4], ANP, MUZ and the DEMATEL methods); relational methods (e.g. ELECTRE, DELPHI and PROMETHEE methods); and many others (e.g. geometric methods), widely described in book [5].

For calculation and analysis, a house with a usable area of 100 m^2, where a floor heating system is to be installed, has been selected. The individual demand for cooking power is 47 W/m^2, with a seasonal heat demand indicator for heating E_A = 64.20 kWh/year·m^2, which according to Austrian guidelines [6] classifies the building as energy-efficient, C class. Also, it was decided to evaluate the execution of this type of heating only on small surfaces up to 20 m^2 (e.g. kitchen + bathroom). Eight variants of underfloor heating covered with cement coats or structural layers described below were adopted for multi-criteria evaluation (more information can be found in the literature related to each system - in squared brackets). These are listed as follows:

1. Traditional radiant floor heating with a heating coil laid in concrete, widely described, e.g. in the catalogue [7, 8].
2. Radiant floor heating with a heating coil laid in thermal insulation grooves, covered with dry screed without heat-dissipating lamellas, described by Zukowski and Karpiesiuk [9].
3. Radiant floor heating with a heating coil laid in thermal insulation grooves, covered with dry screed with heat-dissipating aluminium foil, so-called type B according to standard [10].
4. Radiant floor heating with a heating coil laid in thermal insulation grooves, covered with dry cement screed with heat-dissipating steel lamellas, so-called type B according to standard [10].
5. Lightweight radiant floor heating with a heating coil laid in thermal insulation grooves, covered with an adhesive reinforced with fibreglass mesh layer (without screed) and without heat-dissipating lamellas, as in catalogue [11].
6. Lightweight radiant floor heating with a heating coil laid in thermal insulation grooves, covered with a layer of reactive adhesive (without screed), with heat-dissipating aluminium foil, according to the norm [12].
7. Underfloor electric heating with heating cables laid in the concrete screed, designed as an accumulating system using the second, cheaper night tariff, according to the Vademecum [13].
8. Underfloor electric heating with heating mats laid in the adhesive layer, on the concrete screed with the use of first and second of the electricity tariff, as shown in the Vademecum [13].

2. Criteria for choosing selected variants of underfloor heating

When proceeding to the assessment of the adopted variants we should first select the criteria we are interested in. It is possible to apply both criteria - measurable, expressed in numerical quantities and not measurable for which, either alone or together with experts in the field, we set numerical values to make comparisons and assessments. A criterion is a stimulant if a higher value is positively influenced by the assessment or destimulant when the higher value contributes to the deterioration of the criterion adopted.

2.1. The preliminary set of criteria

Bearing in mind the properties of the underfloor heating system that have an impact on both the investment and the building operation, the so-called preliminary set of criteria (PSC), relevant for the assessment of underfloor heating systems, has been adopted:

- K1 – The cost of the investment for 1 m^2 of the underfloor heating system as a measurable criterion - destimulant;
- K2 – The cost of investment on small surfaces as a measurable criterion - destimulant;
- K3 – The cost of operating the underfloor heating system over a period of 15 years of use as a measurable criterion - destimulant;
- K4 – The total cost of the investment at 100 m^2 and operation over a period of 15 years as a measurable criterion - destimulant;
- K5 – Execution time 100 m^2 of the heating system including the terracotta floor taking into account technological gaps as a measurable criterion- destimulant;
- K6 - The pace of implementation of the heating system as a measurable criterion counted according to 100 m^2/execution time - stimulant;
- K7 – Weight of the heating system at 1 m^2 as a measurable criterion- destimulant;
- K8 – Thermal inertia of the heating system, which translates into the quality of control (less inertia improves control) as a measurable criterion - destimulant;
- K9 – Heat output (thermal efficiency) at a low supply temperature of 35℃ as a measurable criterion - stimulant;
- K10 – The comfort of use depends on the average temperature on the surface of the floor at a temperature of power supply of 35℃ (higher floor temperature relative to the power supply temperature improves comfort) as a measurable criterion - stimulant;
- K11 – The versatility of the workmanship during renovation or retrofitting without removing the concrete primer, which facilitates the construction of new and upgraded facilities as an unmeasurable criterion (a 3-point evaluation scale was adopted) - stimulant;
- K12 – Functional qualities consisting of among others ease of control depending on the thermal inertia of the floor as an unmeasurable criterion (3-point evaluation scale) - stimulant;
- K13 – Ease of installation which affects the speed of implementation of the investment as an unmeasurable criterion (3-point scale of evaluations adopted) - stimulant;
- K14 – Manufacturer's warranty, proving the quality of the materials used as a measurable criterion - stimulant.

The parameters and data needed for the assessment of individual floor heating systems were adopted from the literature mentioned in this article or based on average market values. Average retail and wholesale prices of materials and labour, assuming the use of the same materials and mounting technology, were adopted in the article [14]. The cost of connecting the gas boiler to the water heater was assessed at eight thousand PLN without VAT. When assessing small areas of the rooms, the price of the boiler is not included, assuming its existence during renovation or modernization of the heating. The cost of electric heating systems based on the calculations of the manufacturer of cables and heating mats according to the technology, which is included in the article [14]. The cost of operation, including heating and service costs for 15 years was determined based on the Vademecum [13]. It is assumed that the drying time of concrete is 28 days, and the process of laying heating and terracotta at 100 m^2 lasts 21 days. When deciding on variant 6 with the use of light underfloor heating on the reactive adhesive, this stacking is shorter and is 14 days. In this system, the tiles are immediately laid on the prepared insulating substrate. Thermal inertia was assessed based on the article [15] and thermal performance at a supply temperature of 35℃ was determined based on the tables of Kan-therm system [16]. The thermal resistance of the floor cladding was assumed to be R = 0.15 [$m^2 \cdot K/W$] with high inertia of concrete, and the distance between the coil equal 10 cm.

The uniformity of the temperature distribution on the floor was assessed based on the engineering work [17], articles [9, 18] and catalogue [11]. The non-measurable criteria were assessed based on the numerical values adopted from 1 to 5, assuming the following values for the versatility of workmanship: 1 – impossible, 3 – sometimes, 5 – possible. Numerical assessment of ease of control and installation was made using the following scale: 1 – difficult, 3 – medium, 5 – easy. The non-measurable criteria that were assessed, were guided by the principle that the greater inertia of the floor, makes it difficult to control the floor heating. The results of the assessment show that the assembly of heating systems are better when they do not require heavy construction equipment and when they have a simple installation process because this reduces labour intensity, which in turn lowers time and cost.

The criteria selected above and their analysis are taken from the monograph [19].

2.2. Criteria analysis

To facilitate a pre-accepted analysis of criteria, the quantity of which can be more than a dozen and more is recommended to apply the criteria matrix. Its construction is carried out by analysing individual pairs of criteria. If the criterion contains information about another comparable criterion, then it is given a value of 1 as more significant one and vice versa, the weaker one is assigned a value of 0. Independent criteria that do not have a relationship are equal to 0. As an example, the criterion K4 is the total cost of the building investment and operation, which includes the information on criterion K1 - investment cost and K3 - cost of operation, then the matrix element g (4,1) = 1, element g (1,4) = 0, and g (4,3) = 1, g (3,4) = 0. Another example would be the K12 criterion – ease of control, which informs about the K10 - the comfort of use. Ease of control affects the higher comfort of use so then the element g (12,10) = 1, element g (10,12) = 0.

The global criterion K15 was additionally added to the set of criteria at the end of the matrix in rows and columns. The value 1 is assigned here to the elements of the rows and the value 0 to the elements of the columns. The dependencies between the criteria coded in this way are presented in the form of the matrix G{15,15}, table 1.

Table 1. Matrix G{15,15} - relationship between criteria K1, K2,... K14

Nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	bi
1	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0
4	1	0	1	X	0	0	0	0	0	0	0	0	0	0	0	2
5	0	0	0	0	X	1	0	0	0	0	0	0	0	0	0	1
6	0	0	0	0	0	X	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	X	1	0	0	0	0	0	0	0	1
8	0	0	0	0	0	0	0	X	0	0	0	1	0	0	0	1
9	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0	0

Nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	bi
10	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	1	0	X	0	0	0	1
13	0	0	0	0	1	0	0	0	0	0	0	0	X	0	0	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	X	15
bj	2	1	2	1	2	2	1	2	1	2	1	2	1	1	0	X

Based on the developed matrix, the criteria graph was built. The number of arcs entering and exiting each criterion (vertex) of the graph has been calculated. These values are calculated according to the formulas:

$$b_j = \sum_{i=1}^{n+1} g_{ij} \tag{1}$$

$$b_i = \sum_{j=1}^{n+1} g_{ij} \tag{2}$$

where:

b_i – number of arcs departing from i-vertex,

b_j – number of arcs entering the j-vertex,

g_{ij} – elements in G matrix.

Values b_j and b_j are given in matrix G{15,15} as 16 rows and 16 columns, respectively. Then, ordering layers was performed by using the global criterion K_G (Fig. 1) as a layer 0 of the graph. It connects to the layer 1 criteria, having one entering arc, i.e. the criteria for which b_j=1 in matrix G (Table 1). The following criteria were found there: K2, K4, K7, K9, K11, K13, K14. Arranging the next layers, we select the criteria in order, related only to the criteria above them. Hence, layer 2 graph form K1, K3, K5 and K8, and 3 criteria K6 and K12. The last 4 layer of the graph is the K10 criterion, from which no arches are departing.

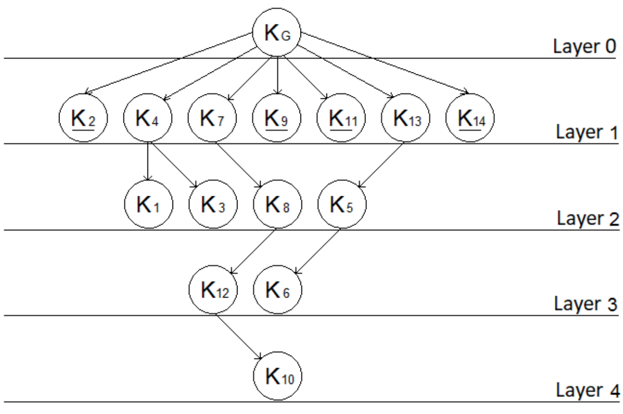

Fig. 1. Criteria graph of G{15,15} matrix

2.3. Designation of the final set of criteria and their values

The elaboration of the criteria graph leads to the designation of the final set, which contributes to the selection of the most important criteria from all the analyses adopted. To the final set of criteria (FSC) only the ones which are related to the global K_G criterion are accepted (underlined in the graph in layer 1), and those whose number of connections in the layer is the largest (layer 2) and these are:

- K1 – Cost of investment for 1 m^2 [PLN]
- K2 – Cost of investment on small surfaces [PLN]
- K3 – Cost of operating the system over a period of 15 years
- K5 – Execution time 100 m^2 of heating system
- K8 – Thermal inertia of the heating system
- K9 – Thermal efficiency
- K11 – Versatility of installation during renovation or modernization
- K14 – Manufacturer's warranty

The FSC values for each of the eight heating variants are set out in table 2 based on the literature data described in section 2 of this article.

Table 2. FSC values of all underfloor heating variants

Criterion* / Variants	K1, d	K2, d	K3, d	K5, d	K8, d	K9, s	K11, s	K14, s
Variant 1	215	240	30150	49	5	53.76	1	10
Variant 2	255	215	30150	21	2.5	51.81	3	10
Variant 3	290	260	30150	21	2	71	3	10
Variant 4	370	390	30150	22	2	87	3	10
Variant 5	230	185	30150	21	1	89	5	10
Variant 6	275	245	30150	14	1	130.1	5	10
Variant 7	120	150	38900	49	5	53.76	1	20
Variant 8	190	240	48725	21	1.5	71.38	5	20

*indications for K: d – destimulant, s – stimulant

2.4. Determining the weightings of criteria

Criteria values do not always have the same validity. The decisive indicator of the selection of the most important and less relevant criteria is the investor's preference and the expert's assessment of the field. Such a choice shall be made by establishing the weighting of the criteria, correcting their measurements. The selection process of the scales can be assisted by e.g. pair analysis. It involves the construction of a square matrix consisting of the FSC, which gives the values according to the investor's preference and the findings of the experts. By summing the rows of the matrix, we get the weight ratio of the criterion in a range from 0-1. The sum of the weights of the criterion always equals 1. Eventually, five sets of weights were adopted so that the most important features of underfloor heating systems can be extracted and these are:

- Set I – validity of the execution time and universality mounting of the systems;
- Set II – validity of the investment cost and thermal efficiency;
- Set III – validity of the investment and operation cost;
- Set IV – installation of heating on a small area (planned renovation);
- Set V – validity of only the investment and operating cost like in III set, omitting other criteria.

In the sets of weights I, II and IV, an analysis of the validity of the vapour was applied. The values of weights in III and V are highest for investment and operation, with the difference that the other criteria are considered less important in the III set, and in V all others are omitted. This was the reason that I-IV was accepted for the general analysis of all weights sets, and V set was treated as confirming the accuracy of the MCDA calculations. Criteria K1 and K2 relate to the same investment costs. The difference is that K1 weights apply to the whole building and K2 to small surfaces. For this reason, when analysing the whole building, the K2 weights are equal to 0 and, for a small investment (e.g. modernisation), the weight K1 = 0. Finally, the following priorities were identified in line with the number of weights and recorded in table 3.

Table 3. Sets of criteria weights

Variants	Set I	Set II	Set III	Set IV	Set V
v_1 – weight of criterion K1	0.091	0.3	0.25	0	0.5
v_2 – weight of criterion K2	0	0	0	0.222	0
v_3 – weight of criterion K3	0.091	0.05	0.25	0.056	0.5
v_4 – weight of criterion K5	0.319	0.05	0.1	0.277	0
v_5 – weight of criterion K8	0.091	0.15	0.1	0.056	0
v_6 – weight of criterion K9	0.091	0.25	0.1	0.056	0
v_7 – weight of criterion K11	0.273	0.1	0.1	0.277	0
v_8 – weight of criterion K14	0.044	0.1	0.1	0.056	0

2.5. MCDA selection and encoding of criteria values

Of the many multiple-criteria analysis algorithms, a corrected summation indicator was selected to include the weightings of the criteria and not requiring that the coded criteria measures have values greater than zero. It shall be determined from the formula:

$$J_i = \sum_{j=1}^{m} Z_{ij} \cdot v_j \tag{3}$$

where:

J_i – summation corrected (synthetic) indicator

Z_{ij} – coded measure of the j-criterion for the i-variant

v_j – weighting of the j-criterion

m – number of criteria

The criteria are sizes with different units of measurement. Therefore, they should be harmonised by coding these values in order to carry out further calculations. The coding process involves the conversion of values to dimensionless, provided a separate action on the criteria of stimulants and destimulants. In this article, you have chosen to normalize with the assumption of maximization. It consists of setting the values of the criteria from decreasing to increasing in the range 0 to 1. For this purpose, the following formulas were used:

- for stimulant

$$z_{ij} = \frac{x_{ij}}{x_{jmax}} \tag{4}$$

- for destimulant

$$z_{ij} = \frac{x'_{ij}}{x'_{jmax}} \tag{5}$$

where

$$x'_{ij} = \frac{1}{x_{ij}} \tag{6}$$

z_{ij} – measure of the i-variant according to the j-criterion
x_{ij} – partial measure of criteria from Table 2
$x'_{j\,max}$ – maximum value of measure j-criterion after maximizing

Using the formulas (6.2) and (6.3), the coded values of all the criteria were calculated and included in table 4.

Table 4. Coded values of criteria measure for eight heating variants

Criteria	K1	K2	K3	K5	K8	K9	K11	K14
Variants	Destimulant					Stimulant		
Variant 1	0.558	0.625	1	0.286	0.2	0.413	0.2	0.5
Variant 2	0.471	0.698	1	0.667	0.4	0.398	0.6	0.5
Variant 3	0.414	0.577	1	0.667	0.5	0.546	0.6	0.5
Variant 4	0.324	0.385	1	0.636	0.5	0.615	0.6	0.5
Variant 5	0.522	0.811	1	0.667	1	0.684	1	0.5
Variant 6	0.436	0.612	1	1	1	1	1	0.5
Variant 7	1	1	0.774	0.286	0.2	0.413	0.2	1
Variant 8	0.632	0.625	0.617	0.667	0.67	0.549	1	1

3. Results

On the basis of the data calculated in table 4, taking into account the weightings of the individual criteria from table 3, the synthetic indicators according to formula (6.1) for the eight underfloor heating variants were calculated and included in table 5.

Table 5. MCDA results of various types of floor heating

Variants	Set I	Set II	Set III	Set IV	Set V
W 1	0.365	0.435	0.549	0.392	0.779
W 2	0.605	0.494	0.624	0.634	0.735
W 3	0.622	0.529	0.635	0.621	0.707

Variants	Set I	Set II	Set III	Set IV	Set V
W 4	0.616	0.531	0.622	0.577	0.662
W 5	0.799	0.711	0.766	0.820	0.761
W 6	0.927	0.781	0.809	0.886	0.718
W 7	0.407	0.606	0.653	0.490	0.887
W 8	0.754	0.691	0.701	0.759	0.625
I place	W 6	W 6	W 6	W 6	W 7
II place	W 5	W 5	W 5	W 5	W 1
III place	W 8	W 8	W 8	W 8	W 5
IV place	W 3	W 7	W 7	W 2	W 2

4. Summary

The following conclusions are drawn from the data in table 5:

1. The MCDA method has allowed the choice of the most advantageous offer of floor heating systems in residential buildings and on small surfaces (up to 20 m^2) for the renovation or modernization of the premises.
2. After the calculation of the summation corrected indicator $\boldsymbol{J_i}$, the best variant for all the criteria with accepted weights and the second and third place has been selected. The best underfloor heating system proved to be a lightweight heating system on reactive adhesive without screed with aluminium foil. Second place was taken by the lightweight heating covered with fiberglass mesh-reinforced glue without screed and without lamellas, and in third place was the electric heating system with heating mats placed in the adhesive layer.
3. Traditional water floor heating system, when we take into account the many criteria of its assessment is not a favourable solution. Only after adopting a set of weights that included only the investment and operating costs (V set of weights in Table 5) was this type of heating beneficial, taking second place. The first place was taken by an electric accumulative heating system using cheaper II electricity tariffs. This only confirms the correctness of the MCDA calculations, as both of these systems, are the cheapest in operation and investment when we omit other criteria for evaluating the heating system.
4. Finally, based on the analysis adopted, it was considered that the best variant of underfloor heating, both when laid down in the entire residential house and on small surfaces, is a **variant 6 – lightweight heating system on the reactive adhesive without screeds with aluminium lamellas.** Also favourable is the lightweight radiant underfloor heating system on the adhesive, reinforced by the fibre mesh layer without screed, taking second MDCA position.

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