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APPLICATION OF AHP AND GRA METHODS IN ENERGY EFFICIENCY POTENTIAL'S ASSESSMENT OF ENVELOPES FROM NATURAL MATERIALS

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The best choice of energy efficient envelope from variety of available materials is still the challenge. Therefore, the attempt of thermal performance multi-criteria evaluation of some building materials of natural origin for energy-efficient envelopes is conducted in present paper. Such types of walls from natural energy-efficient materials are considered in comparison assessment: hempcrete, adobe, strawbale panel, earthbag, cordwood, SIP (plywood+ecofiber), hempcrete+straw and energy efficient block. The influence of thermal inertia time, internal areal heat capacity, as well dimensionless index of thermal inertia *D*, the total thermal resistance of the walls R_{tot}-value, mass of the wall assembly and its cost have been taken into consideration as important influence factors. The multi-criteria numerical assessment of envelope's energy efficiency potential was performed by two popular methods – Analytic Hierarchy Process (AHP) as the subjective weighting method and Grey Relation Analysis (GRA) as the objective weighting method. Both of methods allow to arrange the alternatives and could be applied as decision support tools in decision making (DM) process of choosing the best alternative in terms of multi-criteria assessment. For more objective analysis, by taking into account the variety of physical and physical-mechanical parameters of the wall assembly material, the concept of generalized index of the envelope energy efficiency potential is proposed. Conducted research has shown that the best envelope type in terms of of generalized index of energy efficiency potential has the hempcrete wall and hemcrete+straw wall, almost three times smaller has the wall of the earthbags. The walls from adobe, cordwood and strawbale panels have practically the equal value of generalized index of energy efficiency potential. It could be observed that AHP method shown more inhomogeneous results, than GRA. The possible reason for that is the difference in evaluation attitude in techniques – AHP is considered as the subjective method with pairwise comparison matrixes, while GRA is objective method of comparison.

Key words: AHP method, energy efficiency potential, envelope structures, GRA method, multi-criterial assessment, thermal performance

Introduction

The global energy saving trend on one hand and the sustainable development concept on the other increasingly boosted the usage of multi-criteria decision analysis methods (MCDA) in decision-making. As Wang et al., (2009) stated, "MCDA methods have become increasingly popular … because of the multi-dimensionality of the sustainability goal and the complexity of socio-economic and biophysical systems". As well in this context the usage of building material lead to higher comprehensive responsibility towards further generations. The choice of envelopes construction, elements of ceiling/coating requires the simultaneous analysis of a number of influencing factors (Stazi, 2017; Bläsi, 2001; Wang et al., 2009; Shimray et al., 2017; Tabunshchikov et al., 2002; Fareniuk, 2009). It should be mentioned that variety of multi-dimensional criteria to be compared, and what is the "correct" criterion in the decision making process is still a big issue. The optimal type of envelope's width, type, material for modern building, which is both energy-effective, low cost and environmentally friendly, is still unsolved problem and the challenge (Biks et al., 2019). The same thought has (Stazi, 2017) "...the best solution(s) identification is still an open issue". As a result, there are lot of researches dedicated to the best and appropriate choice of method(s) to make an adequate assessment of different building constructions in terms of sustainable development (Hopfe et al., 2013; Shimray et al., 2017; Kheiri, 2018; Wang et al., 2009) and many others. This paper mainly dealt with the thermophysical parameters of the envelope materials – at steady and unsteady states: the total value of wall assembly thermal resistance R_{tot}-value (m^{2}K/W), the time of thermal inertia (hours) by (Korshunov, Zuev, 2011), the internal areal heat capacity (kJ/m^{2}K) by ISO 13786:2017, the dimensionless thermal inertia indicator D by DBN V. 2.6-31, and some others. The emphasis in this research is made on comparison of envelope's material, primarily made of organic materials which are considered as environmentally friendly. The worldwide trend of multi-criteria assessment in the research of energy efficiency of envelope constructions on the one hand, and tendency of eco-materials solutions that meets sustainable development mainstream in dwelling construction on the other, were the factors, that affected to the writing of present article.

Purpose and tasks of research

To perform a multi-criteria assessment of generalized index of envelope's energy efficiency potential which will be conducted by two independent methods – the Analytical Hierarchy Process (AHP) and Taguchi optimization technique, based on the Grey Relational Analysis (GRA).

Materials and research methodology

Analytical hierarchy Process (AHP)

The use of the AHP method for multi-dimensional analysis of the investigated envelopes types could be significantly helpful in the multi-criteria assessment of an alternative wall type assembly.

The present paper dedicated to the research of the generalized index of the energy efficiency potential-the proposed by the authors criterion which in fact is objective function of six influence factors. Among them are ISO 13786:2017 determined unsteady state thermal performance characteristic – internal thermal areal heat capacity kJ/m^{2}K, steady state's characteristics (the time of thermal inertia τ, hours, the dimensionless index of the envelope thermal inertia D, the total thermal resistance of the envelope R_{tot}-value, m^{2}K/W, as well – mass of the wall, kg/m^2 and costs of the wall materials, €/m^2.

The methodology of creating a hierarchical model for generalized index of energy efficiency potential determining is listed below.

By pairwise comparisons (Saaty, 2009) the advantages of each influence factors have been weighted on the value of the generalized index of energy efficiency potential.

The AHP method calculation steps of the generalized index are as follows.

Step 1. Each of the influence factors is a matrix, which is filled in the next way (Saaty, 2009):

$$A = \begin{bmatrix} 1 \ \ \frac{r_1}{r_2} \ \ \frac{r_1}{r_3} \dots \frac{r_1}{r_n} \\ \frac{r_2}{r_1} \ \ 1 \ \ \frac{r_2}{r_3} \dots \frac{r_2}{r_n} \\ \dots\dots\dots\dots\dots\dots \\ \frac{r_n}{r_1} \ \ \frac{r_n}{r_2} \ \ \frac{r_n}{r_3} \dots 1 \end{bmatrix}, \quad (1)$$

where r_1, r_2, r_3, r_n are the corresponding values of the priorities of the evaluated parameters of the matrix, which characterize the values of six included parameters (the internal areal heat capacity, the time of thermal inertia τ, indicator of the envelope thermal inertia D, the total thermal resistance of the envelope R_{tot}-value, mass of the wall and costs of the wall materials).

By the known line elements of the matrix in Eq. (1), elements of all other lines are calculated. The arbitrary element $a_{jj} = r_i / r_j$, with known elements $a_{kj} = r_k / r_j$, k, and $i = 1,...,n.$ of a certain n-th line, is calculated as $a_{jj} = a_{kj} / a_{ki}$, and $j,k = 1,...,n.$

Step 2. The priority vector of each i-th parameter m_i as the average geometric value of each line of matrix elements divided by the sum of all mean geometric values for the estimated parameters is calculated as below (Saaty, 2009):

$$\sqrt[n]{1 \times \frac{r_1}{r_2} \times \frac{r_1}{r_3} \times ... \times \frac{r_1}{r_n}} = m_1. \tag{2}$$

Step 3. The priorities vector for the first line of the matrix is obtained by the Eq. (1), taking into account the mean of geometric elements of each of the lines is calculated as

$$\frac{m_1}{m_1 + m_2 + ... + m_n} = x_1, \tag{3}$$

where x_1, x_2, ... x_n is the vector of priorities of the first, second, n-th line of the matrix, respectively.

The components of the eigenvector and the vector of priorities for other m_n lines are determined analogically.

Step 4. As the set of relative weights of the alternative, we use the components of our eigenvector λ_{max} corresponding to the maximal characteristic number. Moreover, in order to evaluate the coherence of the matrix, the condition must be fulfilled. As an indicator of the consistency degree of A matrix' elements, the consistency index (CI) is calculated as (Saaty, 2009):

$$CI = \left(\lambda_{max} - n\right) / n - 1, \tag{4}$$

where n is the rank of the matrix.

Step 5. To evaluate the consistency degree adequacy, the consistency ratio (CR) is used and it is calculated as

$$CR = CI \ / \ MRCI, \tag{5}$$

where $MRCI$ – mean random consistency index, is the average value which is randomly calculated for a large number of pairwise matrices that were generated on a fundamental scale (Saaty, 2009).

The resulting vector of the priorities of a certain matrix of pairwise comparisons is considered as acceptable, if the CR does not exceed the coherence threshold in the range of 0.10...0.20.

Step 6. The resulting value V of j-th wall's alternative generalized index in form of normalized additive composition)Saaty, 2009) is calculated in the following manner:

$$V = \sum_{i=1}^{n} a_i \cdot w_i, \tag{6}$$

where a_i – i-th criterion priority, $i = 1,...,n \ n = 6$; w_i – priority vector of alternatives by the i-th criterion.

Grey Relational Analysis (GRA) method

Grey relational method is a branch of grey systems theory developed in 1980 (Lin & Liu, (2004), October) and has been largely applied to MCDA problems in wide range of facilities (Wang et al., 2008; Liu et al., 2017; Sarpkaya & Sabir, 2016; Daniel at al., 2019). Steps of the calculation are as follows.

Step 1. Set of compared data values to be prepared. Thus x_{ij} – analytically calculated value of i-th parameter for j-th wall alternative, $i = 1,2,..,n;\ j = 1,2,...,m;\ n = 6,\ j = 8.$

Step 2. Data to be normalized

Normalization in the theory of grey system projects is called Grey Relational Generating (GRG). The data normalization is considered to be one of the widely used methods of linear data preprocessing (Wang et al., 2009; Daniel et al., 2019; Sarpkaya & Sabir, 2016). It should be normalized according to the specific importance ("The Larger – The Better", "The Smaller – The Better") of the obtained series' criteria.

If the maximum x_{ij} is sought, normalization should be calculated (Sarpkaya & Sabir, 2016) as

$$\hat{x}_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}}, \tag{7}$$

where $\min x_{ij}, \max x_{ij}$ – the minimum and the maximum calculated value of ***i***-th influence parameter for ***j***-th wall alternative in the series;

If the minimum x_{ij} is sought, normalization should be calculated by Eq. (8) as follows (Sarpkaya & Sabir, 2016)

$$\hat{x}_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}}. \quad (8)$$

Step 3. Calculating of Deviation sequences of normalized by Eq. (7), Eq. (8) data series performed in manner (Sarpkaya & Sabir, 2016):

$$ds_{ij} = \hat{x}_{ij} - \max \hat{x}_{ij}. \quad (9)$$

Step 4. Calculating of Grey Relation coefficient (Sarpkaya & Sabir, 2016) as follows in Eq. (10)

$$c_{ij} = \frac{\min ds_{ij} + \xi \cdot \max ds_{ij}}{ds_{ij} + \xi \cdot \max ds_{ij}}, \quad (10)$$

where ξ – is the distinguishing coefficient $0 < \xi < 1$, which is usually 0.5.

Step 5. In order to absence of another output impact on the generalized index's performance, the normalized value of Grey Relational Degree is calculated (Sarpkaya & Sabir, 2016) as below:

$$\gamma_j = \frac{\frac{1}{n}\sum_{i=1}^{n} c_i}{\sum_{j=1}^{m}\frac{1}{n}\sum_{i=1}^{n} c_i}, \quad (11)$$

Thermal performance parameter calculation

The concept of thermal inertia (DSTU N B.V. 2.6-190: 2013; Stazi, 2017; Tabunshchikov et al., 2002; Saulles, 2012) is used as a measure to quantify the heat loss through the building elements. Thermal inertia value is a measure of envelope's heat accumulating capability or the time period during which the temperature stabilization between the external and internal surfaces occurs. As Korshunov & Zuev (2011) stated, for envelopes, which mainly always are multilayered, "…it is impossible to use the dependence of the duration of the quasi-stationary heat-process (time of thermal inertia) in the simple kind for a homogeneous wall" as follows:

$$\tau_u = \pi^{-2} c\rho\delta R, \quad (12)$$

where c – specific heat capacity of the wall material, kJ/kg × m; ρ – the density of the material of the layers of the enclosing structures of walls, kg/m^3; $R = \frac{\delta}{\lambda}$ the thermal resistance of the wall, m^2·K/W; δ – the thickness of the layer of the enclosing structure of the wall, m; λ – thermal conductivity of the envelope material, W/(m·K).

That is a reason, why an analytical dependence for multilayered walls is used for numerical simulation of the thermal inertia time of considered envelopes (Korshunov & Zuev, 2011):

$$\tau_u = \tau_u^{'} L_n, \quad (13)$$

where $\tau_u^{'}$ – the thermal inertia time of a homogeneous wall of thickness δ with parameters of the first layer, which is determined by the dependence as below (Korshunov & Zuev, 2011):

$$\tau_u^{'} = c_i \rho_i \delta^2 / \pi^2 \lambda_i, \quad (14)$$

L_n – layering factor of the envelope which is calculated as (Korshunov & Zuev, 2011):

$$L_n = \{3\delta_{tot}\delta_1^2 - 2\delta_1^3 + \frac{\lambda_1}{c_1\rho_1}\sum_{i=2}^{n} c_i\rho_i\delta_i^2[\frac{\Delta\delta_i}{\lambda_i} + (1 + 2\frac{\Delta\delta_i}{\delta_i})(3\sum_{j=1}^{i-1}\frac{\delta_j}{\lambda_j} + \frac{\delta_i}{\lambda_i})]\}\delta_{tot}^{-3}, \quad (15)$$

where δ_{tot} – general thickness of multilayered envelope, m; δ_1 – the thickness of the multilayered envelope's first layer, m; $\Delta\delta_i = \sum_{j=i+1}^{n} \delta_j$ – the thickness of the multilayered envelope starting from the second layer i = 2, m.

The calculation of the dimensionless index of thermal inertia D was obtained as follows 0)

$$\sum_{i=1}^{n} D_i = \sum (S_i \cdot R_i), \tag{16}$$

where $S_i = \sqrt{\frac{2\pi\lambda_i c_i \rho_i}{T}}$ – the coefficient of heat absorption W/(m^2×K), of i-th layer of the envelope, (Filonenko & Yurin, 2015); T – a period of thermal oscillations, sec.

To determine the coefficient of heat absorption, the 24 h diurnal period of thermal oscillations has been considered, i.e. $T = 24 \cdot 3600 = 86400$ sec.

Numerical analysis

For the numerical simulation and analysis of obtained data were proposed eight types of wall constructions. There are a hempcrete wall (type "A"), an adobe wall (type "B"), a strawbale panel wall (type "C"), an earthbag wall (type "D"), a cordwood wall (type "E"), SIP wall (plywood+ecofiber) (type "F"), combined hempcrete+strawbale wall (type "G") and energy efficient hempcrete block (Biks, Y. et al., 2019) wall (type "H"). The width of all the investigated wall types is 500 mm. The cross sectional schemes of wall types presented as shown below in Fig. 1, 2.

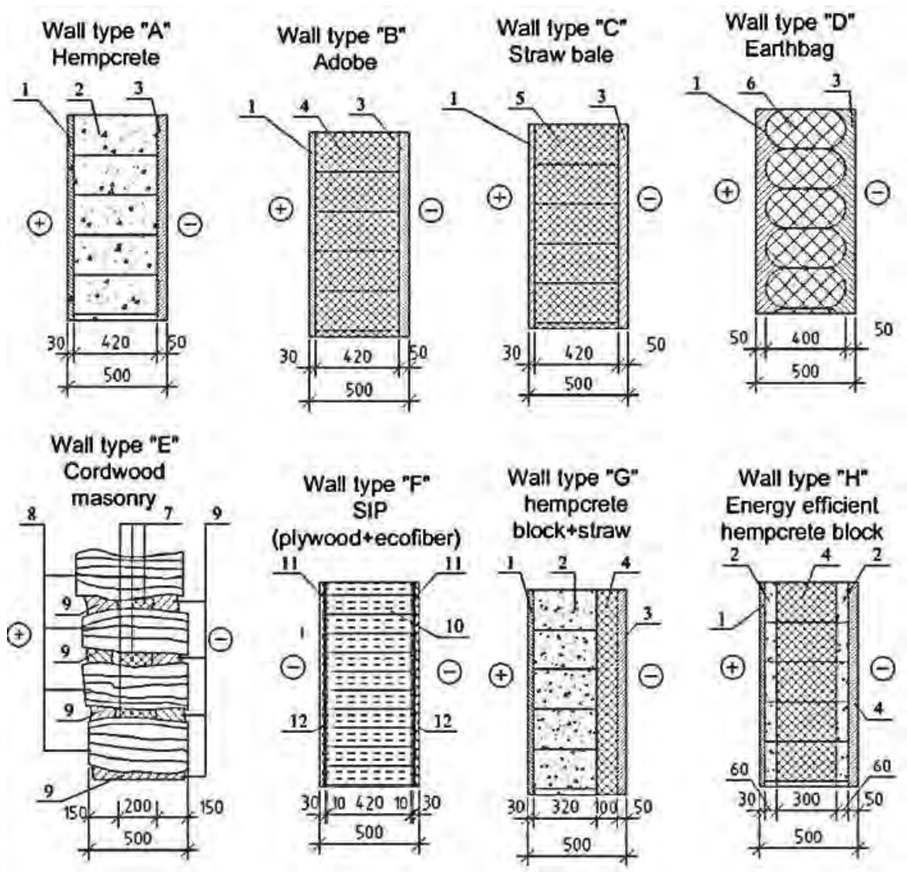

Fig. 1. Cross sectional scheme of considered wall types (1 – internal lime-sand plaster; 2 – hemcrete; 3 – external lime-sand plaster, 4 – adobe; 5 – strawbale panel: 6 – earthbag; 7 – chopped straw as insulator; 8 – cordwood; 9 – lime-sand plaster; 10 – ecofiber; 11 – lime-sand plaster; 12 – plywood)

The costs of materials for proposed wall assemblies was taken from Ukrainian maketplaces' sites with up-to dated averaged prices. The thermophysical and physical characteristics of wall's materials were taken (see Table 1) from referenced literature (Stazi, 2017; Bläsi, 2001; Filonenko&Yurin, 2015; DSTU B.V. 2.6-189: 2013; DSTU-N B.V. 2.6-190: 2013; DBN V. 2.6-31: 2006–2016).

Table 1

The thermophysical, physical and economic characteristics of the envelope's material

Building material	The specific heat capacity c_i, J/(kg·K)	The thermal conductivity λ_i, W/(m·K)	Density ρ_i, kg/m^3	The average cost* of material Q, €/m^3
Hemcprete	1700	0.065	350	75.36
Strawbale panel	1675	0.07	80	75.96
Adobe	880	0.4	1400	18.84
Cordwood*	2146.67	0.5	866.67	75.36
Earthbag	837	1.05	1800	18.09
Plywood	2400	0.18	600	325.55
Ecofiber	1880	0.06	55	45.22
Chopped Straw	1675	0.06	60	9.04
Lime-sand plaster	840	0.81	1600	36.17

* For the calculation purpose the exchange rate of National Bank of Ukraine 1€=33.1744 UAH were assumed.

The analytical computation of internal area heat capacity W/(m^{2}K) performed by a free tool for the calculation of the thermal mass of building components of HTflux. Other parameters were found according to the abovementioned formulae. The total thermal resistance of the envelope R_{tot}-value, m^{2}K/W were calculated assuming the values of internal $R_{si} = 8.7$ m^{2}K/W as well as external $R_{se} = 23.0$ m^2·K/W heat transfer resistance, according to Annex B of DSTU B.V. 2.6-189: 2013. The analytical values of all six significant influence factors of eight wall assemblies have been found and were grouped in Table 2.

Table 2

The calculated features of compared wall assemblies

	Total time of the envelope thermal inertia τ, hours	The indicator of the envelope thermal inertia, D	The total thermal resistance of the envelope R_{tot}-value, m^{2}K/W	The internal areal heat capacity of the envelope, kJ/(m^{2}K)	Mass of the wall m, kg/m^2	Cost of the wall materials, €/m^2
Wall type "A" (Hempcrete)	58.39	12.16	7.14	37.57	300.00	33.59
Wall type "B" (Adobe)	18.77	7.08	1.28	62.76	720.00	11.10
Wall type "C" (Strawbale panel)	13.38	5.82	6.00	57.02	192.00	33.83
Wall type "D" (Earthbag)	10.84	5.18	0.66	68.53	880.00	10.80
Wall type "E" (Cordwood)*	35.01	7.14	4.09	64.20	272.00	24.29
Wall type "F" (SIP panel Plywood+ecofiber)	12.52	5.84	7.34	49.88	131.10	27.53
Wall type "G" (Hempcrete+straw)	47.64	10.31	6.61	45.59	248.00	34.43
Wall type "H" (Energy efficient block)	21.17	7.51	6.39	46.45	194.00	34.55

* All calculations for this wall design are made by taking the following assumptions into account:

1. The ratio of the volumes of clay V_{cl} and wood V_{wood} of the outer and inner layer is 1/3 to 2/3.
2. Wood chocks are from pine (the fibers parallel to the heat flow), clay – sand mortar.
3. Specific heat capacity c_i of the mixed layer construction is found as $(c_{wood} \times V_{wood} + c_{cl} \times V_{cl})/(V_{wood} + V_{cl})$.
4. Other parameters as well as the density and the average thermal conductivity are found by the same dependencies.

Graphical comparison of obtained in Table 2 values for different envelope types are presented in Fig. 2–7.

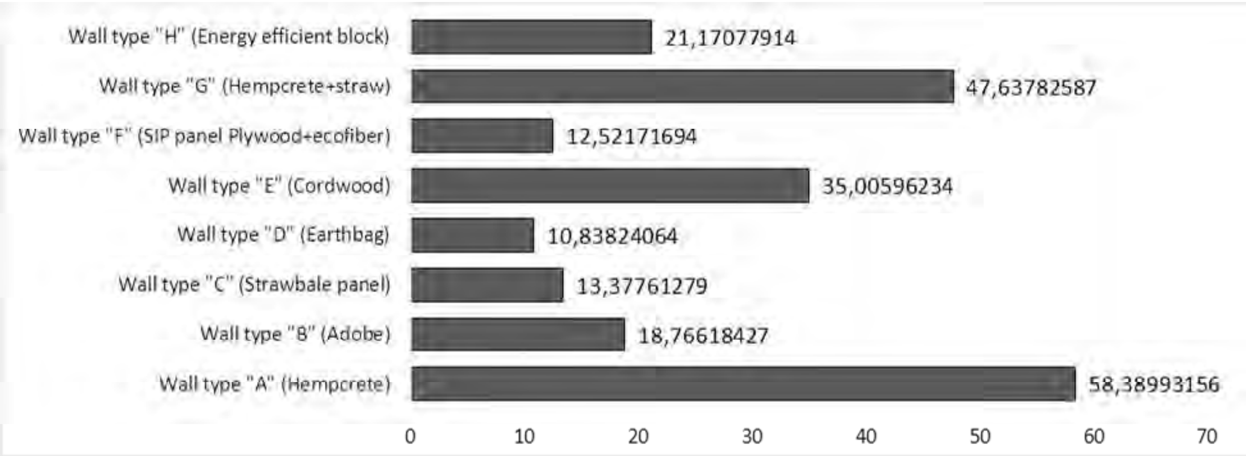

Fig. 2. Total time of the envelope thermal inertia τ, hours

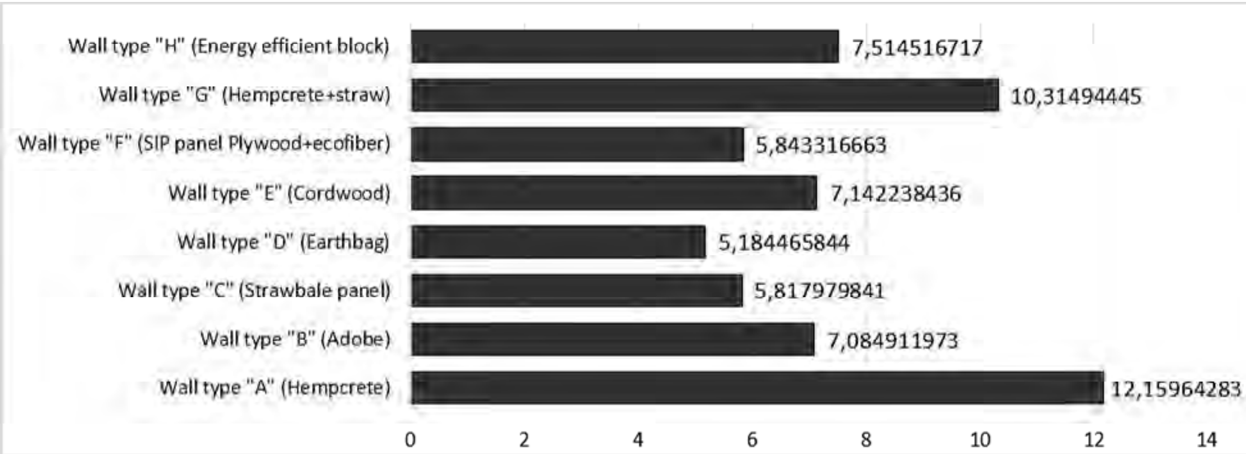

Fig. 3. Index of thermal inertia of walls, D

From the analysis of Fig. 2 and Fig. 3 it could be seen that the dimensionless index of thermal inertia *D* has a good correlation with the data in Fig. 3. From the one hand, for further researches it could be more useful to express one value, for example time of thermal inertia through other, dimensionless one. From the other hand authors acknowledge and agree with same though of Wang et al., (2009) that MCDA methods with use of dependent parameters distorts the objectivity of the overall assessment of generalized index of envelope's energy efficiency potential.

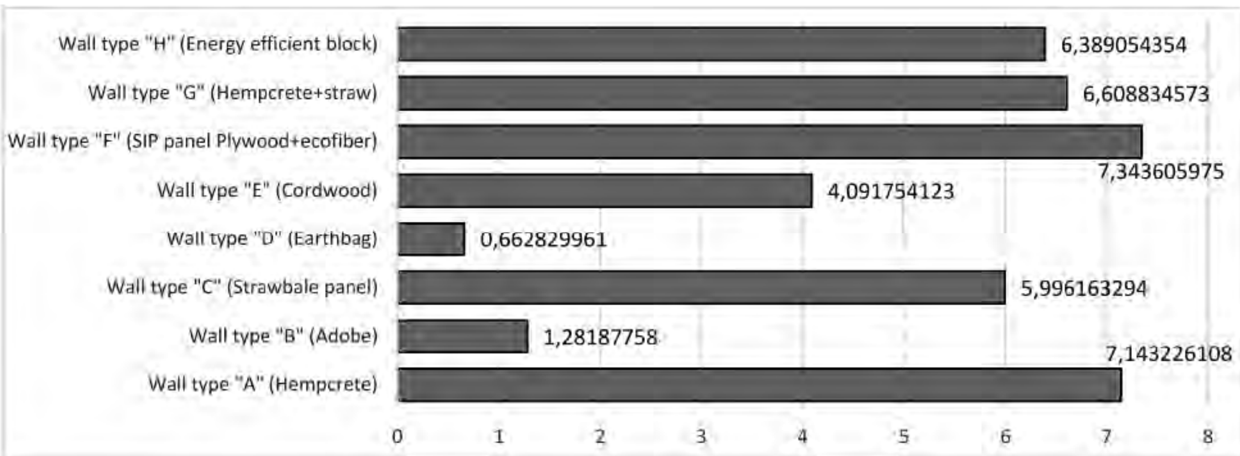

Fig. 4. The total thermal resistance of the walls R_{tot}-value, m^2K/W

Analysis of chart bar graph in the Fig. 4 shown that such walls as type "D" and type "B" could't be applicate for new construction because of their low, unacceptable in terms of R_{tot}-value as it should be ($R_{q,\min}$ = 3.3 m^2·K/W for the First temperature zone, according to Table 3 of DBN V. 2.6-31: 2016). Other wall types are applicable in terms of thermal resistance value. Here (Fig. 4) the correlation between thermal inertia time (Fig. 2) and index (Fig. 3) aren't obvious, that could be explained by difference in thermophysical material's characteristics of particular wall assembly.

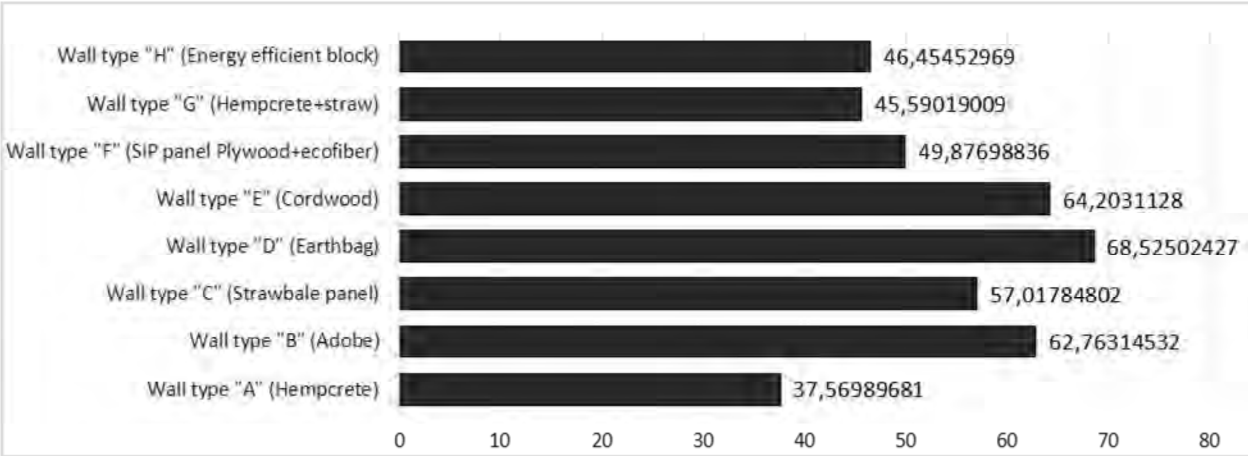

Fig. 5. The internal areal heat capacity of the envelope, kJ/m^{2}K, according to ISO 13786:2017

According to (Brief Guide for the calculation of the thermal mass of building components) "The value of the internal heat-capacity describes the ability of a building component to buffer heat during a diurnal cycle. The value specifies the amount of heat that can be buffered by one square-meter during one day on a temperature swing of 1 degree…". As well, it is highly desirable to maximize the value of the internal heat capacity, to avoid overheating risks in summer, and/or to reduce related cooling costs. From this point, according to presented values on Fig. 5 the best wall assembly type is earthbag (type"D") that correlated to its minimum R_{tot}-value of all proposed wall assemblies from Fig. 4. Such phenomenon could be explained by thermophysical characteristics – its high heat capacity mainly determined by its bulk-density and conductivity, that directly affects the R_{tot}-value.

The challenge is to choose such wall assembly that will be as much highly thermal resistant as well has the biggest areal heat capacity simultaneously.

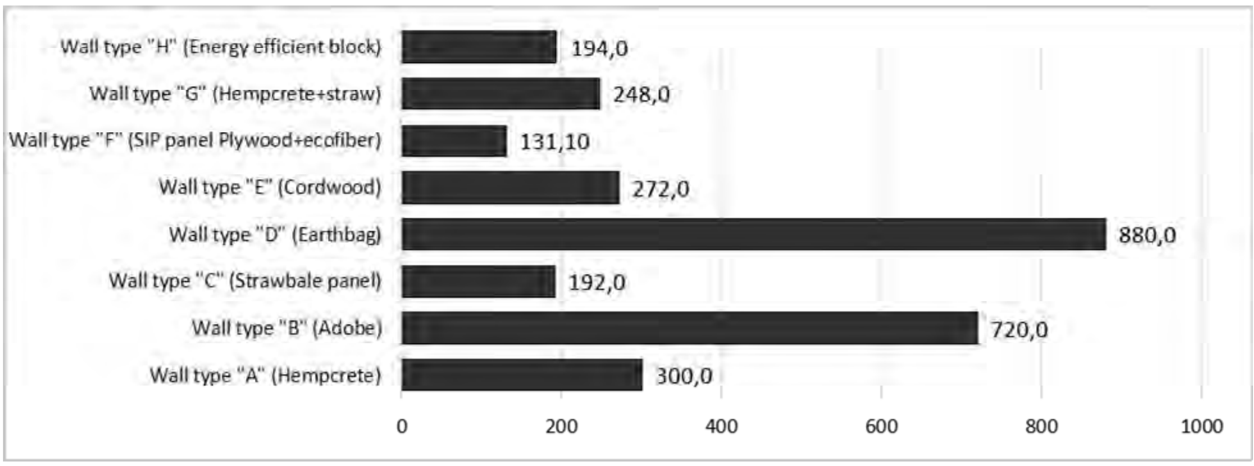

Fig. 6. The mass of the wall assembly, kg/m^2

As it could be considered, the bigger wall assembly mass, obviously, requires more expenses on foundation arrangement. Thus from this point of view the "D" type wall with 880 kg/m^2 is the most expensive, opposite to it there is wall assembly of “F” type with the minimum mass of the wall – 131 kg/m^2 only (see Fig. 6). But in real building practice the correlation between wall mass and fundament cost could be not so one sized and directly proportional as it being considered in first approximation attitude of the article.

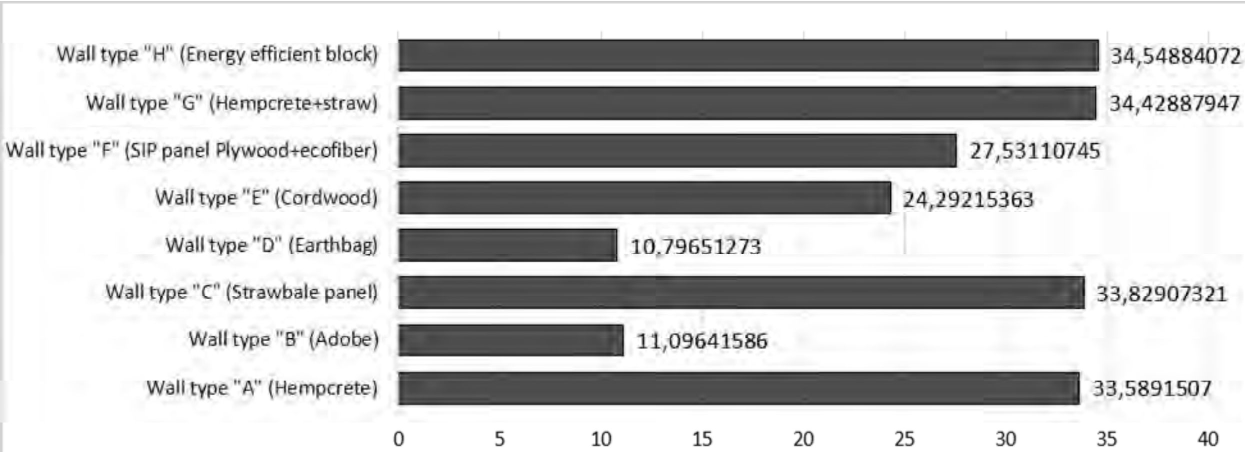

Fig. 7. The Cost of the wall materials, €/m^2

In order to Kulichenko, (2013) the economic criteria is usually the main factor in house material decision making. So, the cheapest / most affordable for construction are wall types “B” and “D” (see Fig. 7). But, by taking into account other parameters, particularly thermophysical aspects of the different assemblies that are calculated in this paper, the optimal and appropriate choice is possible only through processing the MCDA procedure.

To conduct the numerical research and analysis the dimensionless generalized index was proposed by the authors which allows multi-dimensional value’s estimating of various nature characteristics. In present case of study there are thermophysical, economical and physical ones. Thus a three-level hierarchical model, according to AHP (Saaty, 2009) was built to determine the dimensionless generalized index of envelope’s energy efficiency potential (Fig. 8).

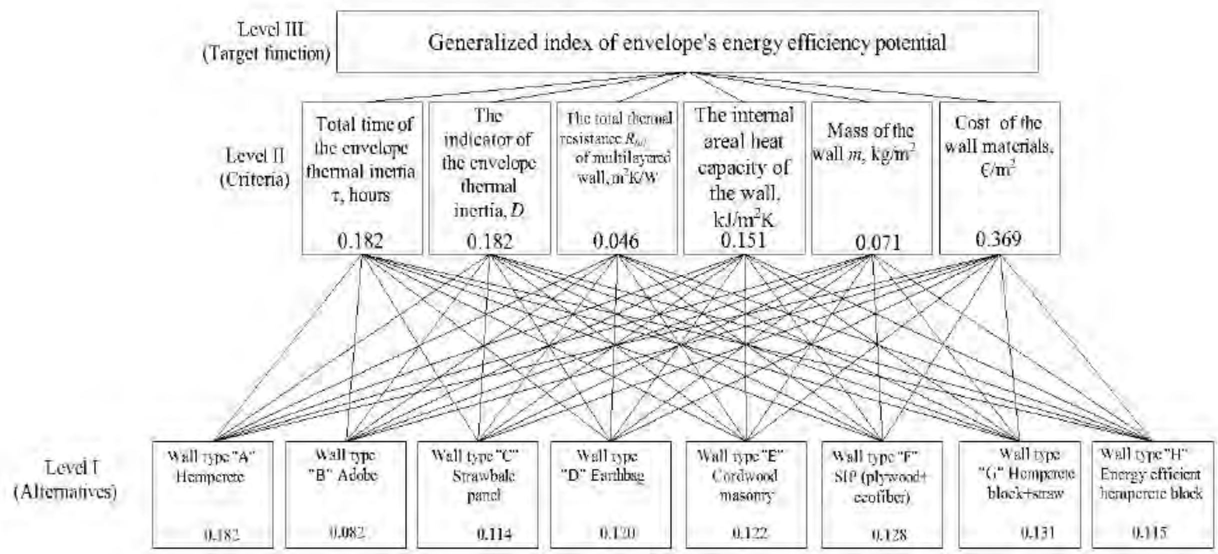

Fig. 8. Hierarchical model of the generalized index of envelope’s energy efficiency potential

According to the abovementioned step by step calculation of AHP multi-criteria assessment's methodology the numbers in Level I rectangles of the hierarchical model are the obtained by Eq. (1)–(6) values of the alternative wall's assembly in terms of proposed criteria (Level II). As well the numbers in Level II rectangles of the hierarchical model are the values of the criteria weight calculated by Eq. (1)–(6) respectively. The filling and finding of all components of the matrix – its eigen vector λ_{max}, the pairwise comparisons, consistency index *CI*, as well as consistency ratio *CR* in example of "Criteria" matrix (Level II) of the hierarchical model (see Fig. 9) are given in Table 4.

Table 4

The pairwise comparison matrix for "Criteria" (Level II of Fig. 1)

Criteria	Total time of the envelope thermal inertia τ, hours	The indicator of the envelope thermal inertia, D	The total thermal resistance of the envelope R_{tot}-value, m^2K/W	The internal areal heat capacity of the envelope, $kJ/(m^2K)$	Mass of the wall m, kg/m^2	Cost of the wall materials, €/m^2	Criterion weight	Normalized value of Criterion weight
Total time of the envelope thermal inertia τ, hours	1	1	4	1	3	1/2	1.348	0.182
The indicator of the envelope thermal inertia, D	1	1	4	1	3	1/2	1.348	0.182
The total thermal resistance of the envelope R_{tot} -value, m^2K/W	1/4	1/4	1	1/3	1/2	1/7	0.338	0.046
The internal areal heat capacity of the envelope, $kJ/(m^2K)$	1	1	3	1	2	1/3	1.122	0.151
Mass of the wall m, kg/m^2	1/3	1/3	2	1/2	1	1/5	0.530	0.071
Cost of the wall materials, €/m^2	2	2	7	3	5	1	2.737	0.369
The eigenvector λ_{max}= 6.039	Consistency index *CI*=0.196			Consistency ratio *CR*=0.158				

In this matrix (Table 4), in each cell, the expert assessments of the benefits of the influence factors has been arranged by the widely popular 9-point Saaty scale (Saaty, 2009). In addition, the filling of the matrix (Table 4) is carried out according to the rule: the number of more than one is put in a cell if the evaluated criterion on the left has an advantage over the criterion above it on the desired parameter. Numbers less than one are placed in the corresponding cells if the evaluated parameter on the left has a lower advantage over the estimated criterion over the parameter above it. To determine the generalized index of wall assembly's energy efficiency potential (level III, Fig. 9) for particular wall alternative, the resulted value of each local vector of the normalized criterion weight (the last column in Table 4) of each of the influencing factors (level II, Fig. 9) is multiplied by the global vector of alternatives weight and after this all the values is summed. Resulted values in presented as numbers at Level I rectangles in Fig. 9. All the weights of the criteria weights for the rest of matrices and factors of influence have been found on the same manner. For better visualization of results that have been calculated by Eq. (1)–(6), the chart bar graph is proposed on Fig. 9.

The energy efficiency analysis of wall assemblies performed by AHP reveals, that the best solution is "G" type wall assembly (hempcrete+straw) with V = 0.188, and the nearest value has the "A" type wall from hempcrete with V = 0.182. The worst solution is "D" type wall from earthbag with value V=0.064, that is almost three times less than the best variant "A".

To provide an additional comparison of the evaluated by AHP values of generalized index of energy efficient potential, the GRA method was applied as described in Eq. (7)–(11) and presented below. In Table 5 are shown normalized by Eq. (7), (8) values of investigated features of wall assemblies (Table 2).

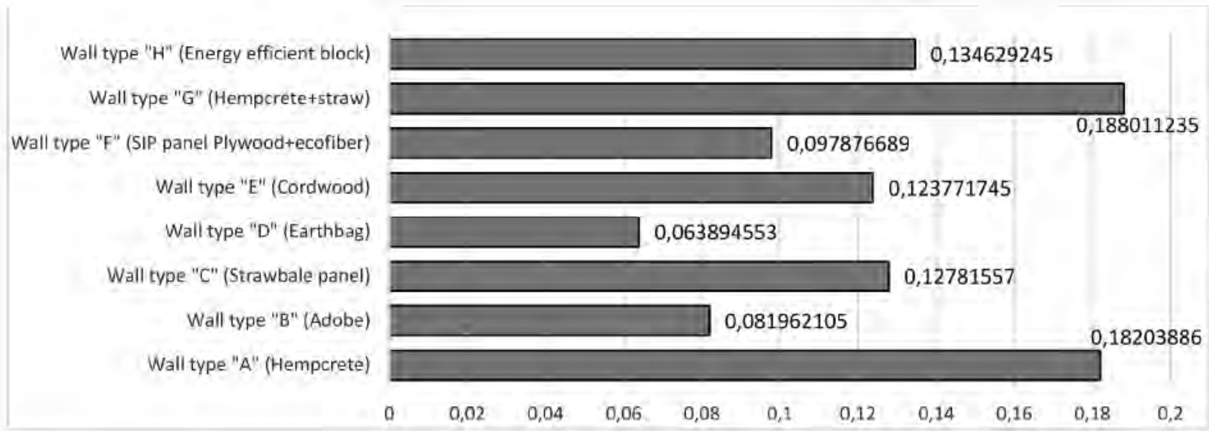

Fig. 9. The generalized index of envelope's energy efficiency potential performed by AHP

Table 5

The normalized features of compared wall assemblies

Wall type	Total time of the envelope thermal inertia τ, hours	The indicator of the envelope thermal inertia, D	The total thermal resistance of the envelope R_{tot}-value, m^2K/W	The internal areal heat capacity of the envelope, $kJ/(m^2K)$	Mass of the wall m, kg/m^2	Cost of the wall materials, €/m^2
Wall type "A" (Hempcrete)	1.000	1.000	0.970	0.000	0.774	0.040
Wall type "B" (Adobe)	0.167	0.272	0.093	0.814	0.214	0.987
Wall type "C" (Strawbale panel)	0.053	0.091	0.798	0.628	0.919	0.030
Wall type "D" (Earthbag)	0.000	0.000	0.000	1.000	0.000	1.000
Wall type "E" (Cordwood)	0.508	0.281	0.513	0.860	0.812	0.432
Wall type "F" (SIP panel Plywood+ecofiber)	0.035	0.094	1.000	0.398	1.000	0.295
Wall type "G" (Hempcrete+straw)	0.774	0.736	0.890	0.259	0.844	0.005
Wall type "H" (Energy efficient block)	0.217	0.334	0.857	0.287	0.916	0.000

In Table 6 deviation sequences according to Eq. (9) of abovementioned data (Table 5) are shown.

Table 6

The deviation sequences of compared wall assemblies

Wall type	Total time of the envelope thermal inertia τ, hours	The indicator of the envelope thermal inertia, D	The total thermal resistance of the envelope R_{tot}-value, m^2K/W	The internal areal heat capacity of the envelope, $kJ/(m^2K)$	Mass of the wall m, kg/m^2	Cost of the wall materials, €/m^2
Wall type "A" (Hempcrete)	0.000	0.000	0.030	1.000	0.226	0.960
Wall type "B" (Adobe)	0.833	0.728	0.907	0.186	0.786	0.013
Wall type "C" (Strawbale panel)	0.947	0.909	0.202	0.372	0.081	0.970
Wall type "D" (Earthbag)	1.000	1.000	1.000	0.000	1.000	0.000
Wall type "E" (Cordwood)	0.492	0.719	0.487	0.140	0.188	0.568
Wall type "F" (SIP panel Plywood+ecofiber)	0.965	0.906	0.000	0.602	0.000	0.705
Wall type "G" (Hempcrete+straw)	0.226	0.264	0.110	0.741	0.156	0.995
Wall type "H" (Energy efficient block)	0.783	0.666	0.143	0.713	0.084	1.000

Table 7 shows the GRA coefficients and grades according to Eq. (10), (11).

Table 7

The GRA coefficients and normalized grades of wall assemblies

Wall type	Total time of the envelope thermal inertia τ, hours	The indicator of the envelope thermal inertia, *D*	The total thermal resistance of the envelope R_{tot}-value, m^2K/W	The internal areal heat capacity of the envelope, $kJ/(m^2K)$	Mass of the wall *m*, kg/m^2	Cost of the wall materials, €/m^2	Grey relation Grade	Normalized values of Grey relation Grade
Wall type “A” (Hempcrete)	1.000	1.000	0.943	0.333	0.689	0.343	0.718	0.155
Wall type “B” (Adobe)	0.375	0.407	0.355	0.729	0.389	0.975	0.538	0.116
Wall type “C” (Strawbale panel)	0.346	0.355	0.713	0.574	0.860	0.340	0.531	0.114
Wall type “D” (Earthbag)	0.333	0.333	0.333	1.000	0.333	1.000	0.556	0.120
Wall type “E” (Cordwood)	0.504	0.410	0.507	0.782	0.727	0.468	0.566	0.122
Wall type “F” (SIP panel Plywood+ecofiber)	0.341	0.356	1.000	0.454	1.000	0.415	0.594	0.128
Wall type “G” (Hempcrete+straw)	0.689	0.654	0.820	0.403	0.762	0.334	0.610	0.131
Wall type “H” (Energy efficient block)	0.390	0.429	0.778	0.412	0.856	0.333	0.533	0.115

Comparison of obtained values of generalized index of walls energy efficient potential conducted by two MCDA techniques are shown in Fig. 10.

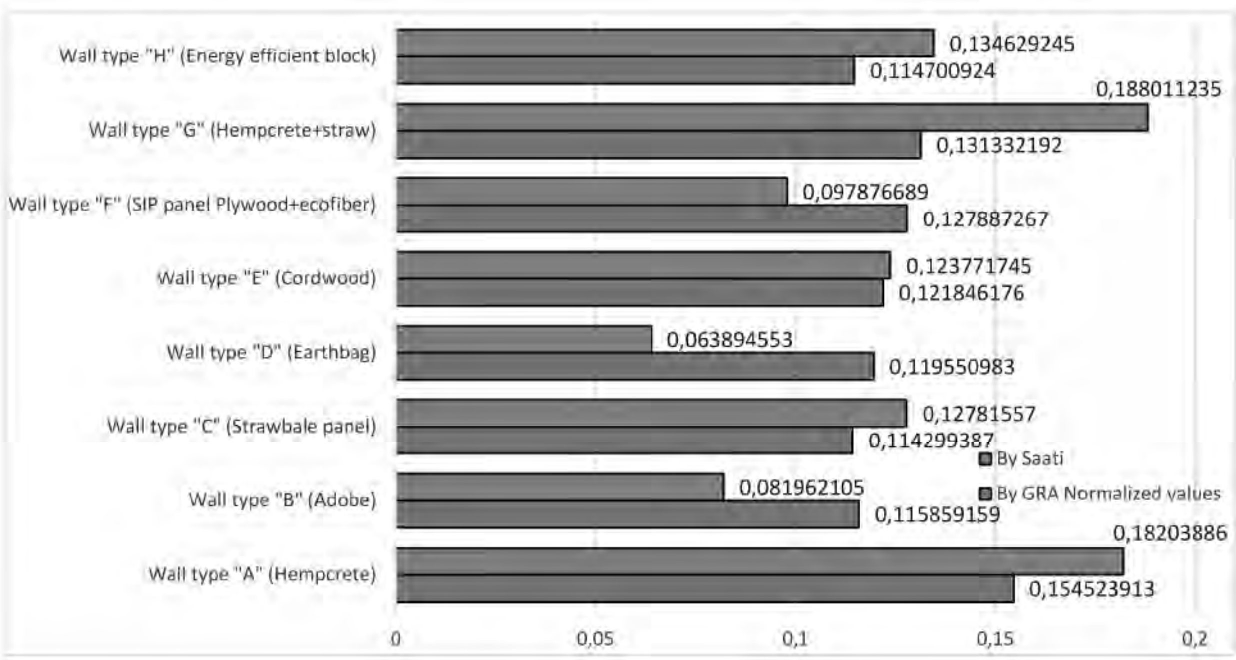

Fig. 10. Generalized index of envelope’s energy efficiency potential which is calculated by AHP and GRA techniques

From the Fig. 10 it could be concluded that AHP method shown more inhomogeneous results, than GRA. The possible reason for that is the difference in evaluation attitude in techniques – AHP is considered as the subjective method, while GRA is objective method of comparison.

Discussion of the results of the study

Analysis of results (Fig. 10) reveals that only the “E” wall type (cordwood) has the minimal value divergence. The larger difference in assessment approximately twice as much, are observed in the “D” wall type (earthbag). The probable reason for such difference in values could be explained by the biased subjective evaluation that took place in pairwise comparison matrixes. The values obtained for “H”, “C” “F” wall type has slight differences between results according to proposed techniques. From the other hand in both multi-criteria comparison techniques the first two types of wall assemblies are the “A” and “G” alternatives. Without detracting from the above it should be mentioned that the more MCDA methods will be involved into comparative research, the more objective will be the evaluation performance.

Although the presented results for this particular analysis cannot be applied to every choice case, and assessment of the generalized index of energy efficiency potential should be verified and improved in some aspects, for example in the supplement, further development and “correct” detecting of the significant evaluation criteria (climate factor, the lifetime of the wall construction / whole building without overhaul, etc.), it is believed that if this procedure is applied correctly and in combination with other MCDA techniques, such as the combination weighting method, this multi-criteria model approach can become a powerful tool to help the decision making person to make an optimal selection in particular application.

Conclusions

1. The application of MCDA methods is widely popular in modern researches which deal with uncertain data in field of energy efficiency assessment.
2. AHP method of assessment of the generalized index of envelope’s energy efficiency potential shown more inhomogeneous results, than GRA. The possible reason for that could be the difference in evaluation attitude in specific techniques – in AHP method it could be the biased subjective evaluation which took place in pairwise comparison matrixes.
3. According to results analysis, both of the multi-criteria comparison techniques shown the best two types of wall alternatives – the hempcrete and hempcrete+straw.
4. The worst wall assembly is still uncertain, because of significant differences in compared values.

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ВИКОРИСТАННЯ МЕТОДУ АНАЛІЗУ ІЄРАРХІЙ (AHP) ТА СІРОГО РЕЛЯЦІЙНОГО АНАЛІЗУ(GRA) ДЛЯ ОЦІНКИ ЕНЕРГОЕФЕКТИВНОСТІ ОГОРОДЖУВАЛЬНИХ КОНСТРУКЦІЙ З ПРИРОДНИХ МАТЕРІАЛІВ

Найкращий вибір енергоефективних огороджувальних конструкцій з різноманітних доступних матеріалів залишається проблемою. Тому в цій роботі проведена спроба багатокритеріальної оцінки теплотехнічних характеристик деяких будівельних матеріалів природного походження для енергоефективних огороджувальних конструкцій. Наступні типи стін з природних енергоефективних матеріалів розглянуто в порівняльній оцінці: арболіт, саман, панель із солом’яних блоків, землебит, чуркобетон, СІП панель зековатою, арболіт+солома та енергоефективний теплоблок. Проаналізовано вплив часу теплової інерції τ, теплоємності внутрішньої площі, показника теплової інерції *D*, загальної величини термічного опору R_{tot}, вартості матеріалів стін та їхню вагу. Багатокритеріальну чисельну оцінку потенціалу енергоефективності огороджувальної конструкції проводили двома популярними методами – методом аналізу ієрархій (МАІ) як суб’єктивним методом та методом сірого реляційного аналізу (СРА) як об’єктивним методом. Обидва методи дозволяють упорядкувати альтернативи та можуть бути застосовані як інструменти підтримки прийняття рішень у процесі прийняття рішень у виборі найкращої альтернативи з точки зору багатокритеріальної оцінки. Проведені за двома незалежними методиками дослідження показали, що найкращим типом огороджувальної конструкції з точки зору запропонованих критеріїв, є стіна з арболіту а також з арболіту+соломи, майже втричі менший потенціал має стіна із землебиту. Стіни з чуркобетону, енергоефективного теплоблоку та солом’яних панелей, що оцінені за двома методиками мають практично однаковий узагальнений індекс потенціалу енергоефективності. Для більш об’єктивного аналізу, беручи до уваги різноманітність фізичних та фізико-механічних параметрів матеріалу огороджувальних конструкцій стін, запропоновано узагальнений індекс потенціалу енергоефективності огороджувальних конструкцій. Оцінка узагальненого індексу потенціалу енергоефективності розрахована за двома методиками показала, що за МАІ показники мають більш неоднорідні значення величин, що може бути пояснено суб’єктивністю в оцінці при проведенні процедури парних порівнянь альтернатив.

Ключові слова: МАІ, потенціал енергоефективності, огороджувальні конструкції, метод с узагальнений індекс потенціалу, СРА, багатокритеріальна оцінка, теплотехнічні характеристики.