

ENERGY PERFORMANCE ASSESSMENT OF ENVELOPES FROM ORGANIC MATERIALS

Yuriy BIKS^a, Georgiy RATUSHNYAK^b, Olga RATUSHNYAK^c

^a PhD; Department of Construction, Architecture and Municipal Economy, Vinnytsia National Technical University, Voiniv Internatsionalistiv, 7. Vinnytsia, 21000 Ukraine
E-mail address: biksyuriy@gmail.com

^b PhD, Prof.; Department of Engineering Systems in Construction, Vinnytsia National Technical University, Voiniv Internatsionalistiv, 7. Vinnytsia, 21000 Ukraine
E-mail address: ratusnakg@gmail.com

^c PhD, Associated Prof.; Department of Enterprise Economics and Production Management, Vinnytsia National Technical University, Khmelnyts'ke shosse, 95. Vinnytsia, 21000 Ukraine
E-mail address: ogratushnyak@gmail.com

Received: 13.02.2019; Revised: 29.04.2019; Accepted: 6.06.2019

Abstract

The paper estimates the thermal performance of effective building envelopes from organic materials for the construction of low-rise buildings. The popular types of walls made of natural energy-efficient materials with low carbon footprint are considered in numerical assessment: hempcrete, adobe, strawbale panel, earthbag and cordwood. The influence of the constructive layer type of the envelope on the amount of thermal inertia time is analyzed. It is revealed that the hempcrete wall has the biggest thermal inertia time, the wall of the earthbags has almost ten times smaller. The walls made of adobe and strawbale panels have practically equal time of thermal inertia. For more objective analysis, by taking into account the variety of physical and physical-mechanical parameters of the envelopes' material, the concept of integral criterion of the envelope energy efficiency potential is proposed. The estimation of the integral criterion of energy efficiency potential is calculated by the Analytic Hierarchy Process and the proposed method is fulfilled. Comparison of the integral criterion of energy efficiency potential for different wall types which was made by means of two abovementioned methods has shown the same order of magnitude.

Keywords: Energy efficiency potential; Enveloping structures; Integral criterion; Organic materials; Thermal inertia.

1. INTRODUCTION

The global trend of organic materials application for the construction low rise residential accommodation in the context of the sustainable development concept results in growing interest towards the usage of both known natural materials and their combinations as well as the search of new technological decisions. The trend of eco-buildings is starting to play an important role. The concept of eco-buildings means construction

of low-energy buildings [1] that cause less harm to the environment due to minimised value of primary energy consumption and low rate of heat losses, cost of materials, etc. As Brojan, L. *et al* [2] states, one of the criteria, which can be applied for the assessment of environment damage, is an index of primary energy consumption, or primary energy input (PEI) index, MJ/m². In fact, this is the volume of necessary energy resources for the production and maintenance of a 1 m² surface of enclosing structures [2].

It is obvious that eco-buildings should be primarily constructed of organic materials, which meet all abovementioned requirements. The worldwide spreading of this trend in general, and in Ukraine, in particular, is becoming of special significance.

2. ANALYSIS OF LITERARY DATA AND PROBLEM STATEMENT

2.1. Heat losses

The heat losses in buildings (kW/m^2), as one of the significant characteristics which directly influences energy-efficient building level [3] could be taken as another criterion which can help in choosing envelopes construction. According to Lapin, Y. N. [4], with a few exceptions, all energy costs of the building are thermal by nature, since almost all the energy emitted in the house – mechanical, electrical or radiant passes into a thermal form before leaving the building.

The heat-power energy in the low-rise buildings is generally lost in three main directions (Fig. 1):

- through opaque enclosures (walls, floor, ceiling);
- through translucent enclosing structures (windows, rooflights);
- due to ventilation.

According to the results of various authors' studies [4, 5, 6] the analysis of the distribution of heat losses in a single-storey building (Fig. 1), shows that the accumulated losses of heat have one order. Furthermore, the data [5] represented in Fig. 1 relates to a building that has not been subjected to modern heat protection requirements yet.

According to Bläzi V. [5], the main losses depend on the type of the building, its configuration and other parameters. Thus, the percentage of the heat which is lost through the chimney will be 32%, through the windows – 28% (with 20% – through glass and frames, 8% – through gaps and slots in windows and ventilation), 18% – through the walls, 16% – through the roof, and 6% – through the basement) [5]. Probably, general ratio of heat losses do not depend on the type of envelope material.

2.2. Materials and influence factors

The most commonly known technologies and natural materials of organic origin for the energy-efficient “green” buildings can be defined as the following:

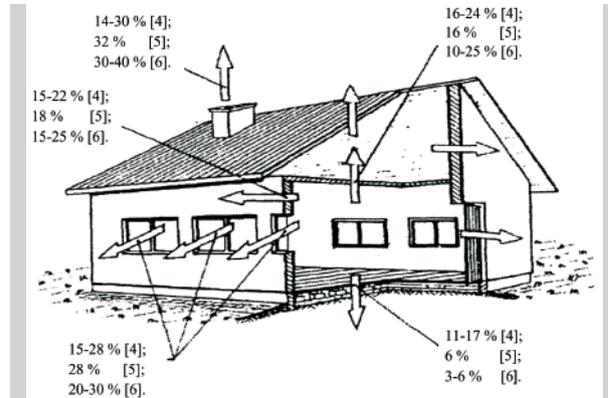


Figure 1. Estimated distribution of heat losses in the house according to data [4, 5, 6]

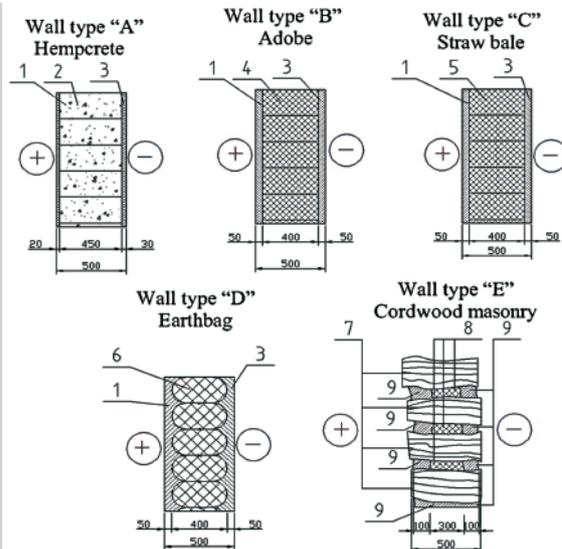


Figure 2. Wall types “A”...“E” for numerical modelling (1 – internal lime-sand plaster; 2 – straw bales; 3 – external lime-sand plaster; 4 – adobe blocks; 5 – straw bales; 6 – bags with tamped soil; 7 – cordwood; 8 – insulation (chopped straw); 9 – lime-sand plaster)

- adobe which has been known for centuries [7];
- prefabricated or monolithic hempcrete [8, 9, 10];
- wooden frame buildings (logs, double skeleton with effective insulation);
- earthbag (the use of soil in bags as building material for bearing walls [11, 12]);
- straw bales (non loadbearing strawbale system or loadbearing “Nebraska style” type) or modern prefabricated straw panels [13, 14];
- peat blocks (“Geocar” type) [15] and many others can be mentioned.

An optimal decision regarding the material of envelopes should be made by simultaneous comparison of the main thermophysical, physical-mechanical characteristics of materials, as well as some economic factors. On the other hand, in case of uncertainty, various theoretical models and algorithms should be used in decision making process, as it is shown by Sheina, S. G. [16], Matsura A. A. [17], Smirnova, S. N. [18].

Many authors [2, 4, 13, 16, 19, 20] are unanimous in the fact, that the proper choice of materials for the envelopes erection, elements of ceiling/coating in terms of energy-effectiveness, low cost, minimum of heat losses and environmental friendliness are still an unsolved problem. Moreover, nowadays we have a challenge that requires a simultaneous analysis of a number of influencing factors. On the other hand, the determinative factor in this challenge is usually of an economic nature [13]. However, environmental, physiological and aesthetic components should also be considered [18].

3. PURPOSE AND TASKS OF THE RESEARCH

The purpose of the current research is to provide an objective comparison of different types of envelopes from natural materials of organic origin in terms of their thermophysical and physical-mechanical parameters.

To achieve this goal, a variety of the following tasks should be solved:

- a list of envelopes' types for low storey residential buildings, based on the conducted data review should be created;

- multi-criteria evaluation of the parameters of each of the investigated variants of the envelopes installation should be proposed;
- the adequacy of the obtained multi-criteria evaluation values should be checked on a different mathematical apparatus.

4. MATERIALS AND METHODS OF THE RESEARCH

For numerical simulation and further analysis, as well as for the convenient calculation of the research purpose five blank wall cross sections types of walls from natural materials of an organic origin (Fig. 2) are used: a hempcrete wall (type "A"), an adobe wall of (type "B"), a strawbale panel wall (type "C"), an earthbag wall (type "D") and a cordwood wall (type "E") with the corresponding thermophysical and physical-mechanical characteristics of the structural layers (Table 1-5). In addition, for an objective assessment, the thickness of the whole walls is taken to be equal to 500 mm. To define a specific pressure on the foundation, the mass of 1 m² of the wall is divided by a wall width of 0.5 m. All dimensions presented in Fig. 2 are in mm.

The concept of the thermal inertia [23, 25, 26] is used to quantify the heat loss through the walls of the building, which shows how efficient the construction is in terms of the time period during which the stabilization of the temperature of the external and internal surfaces of the wall takes place. Korshunov O. states [26] that 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 for envelopes, which, in fact, are

Table 1.
Thermophysical and physical-mechanical characteristics of the wall layers (type "A")

| Thermophysical and physical-mechanical characteristics of the wall layers | Constructive wall layer starting from the inside of the room | | |
|--|--|---------------------|------------------------------|
| | Inside lime – sandy plaster | Hempcrete from flax | Outside lime – sandy plaster |
| The specific heat capacity of the material of the layer, c_i (J/kgK) [21, 22] | 840 | 2300 | 840 |
| The thickness of the layer, δ_i (m) | 0.02 | 0.45 | 0.03 |
| Density of the layer ρ_i , (kg/m ³) [21, 22] | 1600 | 550 | 1600 |
| The weight of 1m ² wall, kg | 32 | 247.5 | 48 |
| The thermal conductivity of the layer λ_i , (W/mK) [21, 22] | 0.81 | 0.075 | 0.81 |
| The coefficient of heat absorption of the i -th layer, S_i (W/m ² K) [23] | 8.90 | 2.63 | 8.90 |
| The thermal resistance of the i -th layer, R_i (m ² K/W) | 0.025 | 6.000 | 0.037 |
| An indicator of thermal inertia of the of the i -th layer D_i by the formula (5) | 0.22 | 15.76 | 0.33 |

Table 2.
Thermophysical and physical-mechanical characteristics of the wall layers (type “B”)

| Thermophysical and physical-mechanical characteristics of the wall layers | Constructive wall layer starting from the inside of the room | | |
|---|--|-------|------------------------------|
| | Inside lime – sandy plaster | Adobe | Outside lime – sandy plaster |
| The specific heat capacity of the material of the layer, c_i (J/kg×K) [7, 21, 22] | 840 | 880 | 840 |
| The thickness of the layer, δ_i (m) | 0.05 | 0.4 | 0.05 |
| Density of the layer ρ_i , (kg/m ³) [21, 22] | 1600 | 1400 | 1600 |
| The weight of 1m ² wall, kg | 80 | 560 | 80 |
| The thermal conductivity of the layer λ_i , (W/mK) [21, 22] | 0.81 | 0.4 | 0.81 |
| The coefficient of heat absorption of the i -th layer S_i (W/m ² K) [23] | 8.90 | 5.99 | 8.90 |
| The thermal resistance of the i -th layer, R_i (m ² K/W) | 0.062 | 1.000 | 0.062 |
| An indicator of the thermal inertia of the i -th layer D_i by the formula (5) | 0.55 | 5.99 | 0.55 |

Table 3.
Thermophysical and physical-mechanical characteristics of the wall layers (type “C”)

| Thermophysical and physical-mechanical characteristics of the wall layers | Constructive wall layer starting from the inside of the room | | |
|---|--|-----------------|------------------------------|
| | Inside lime – sandy plaster | Strawbale panel | Outside lime – sandy plaster |
| The specific heat capacity of the material of the layer, c_i (J/kg×K) [7, 21, 22] | 840 | 1675.00 | 840 |
| The thickness of the layer, δ_i (m) | 0.05 | 0.40 | 0.05 |
| Density of the layer ρ_i , (kg/m ³) [21, 22, 24, 25] | 1600 | 120.00 | 1600 |
| The weight of 1m ² wall, kg | 80 | 47.40 | 80 |
| The thermal conductivity of the layer λ_i , (W/mK) [21, 22, 24, 25] | 0.81 | 0.07 | 0.81 |
| The coefficient of heat absorption of the i -th layer S_i (W/m ² K) [23] | 8.90 | 0.97 | 8.90 |
| The thermal resistance of the i -th layer, R_i (m ² K/W) | 0.062 | 6.08 | 0.062 |
| An indicator of the thermal inertia of the i -th layer D_i by the formula (5) | 0.55 | 5.92 | 0.55 |

Table 4.
Thermophysical and physical-mechanical characteristics of the wall layers (type “D”)

| Thermophysical and physical-mechanical characteristics of the wall layers | Constructive wall layer starting from the inside of the room | | |
|---|--|-----------------|------------------------------|
| | Inside lime – sandy plaster | Strawbale panel | Outside lime – sandy plaster |
| The specific heat capacity of the material of the layer, c_i (J/kg×K) [7, 21, 22] | 840 | 1675.00 | 840 |
| The thickness of the layer, δ_i (m) | 0.05 | 0.40 | 0.05 |
| Density of the layer ρ_i , (kg/m ³) [21, 22, 24, 25] | 1600 | 120.00 | 1600 |
| The weight of 1m ² wall, kg | 80 | 47.40 | 80 |
| The thermal conductivity of the layer λ_i , (W/mK) [21, 22, 24, 25] | 0.81 | 0.07 | 0.81 |
| The coefficient of heat absorption of the i -th layer S_i (W/m ² K) [23] | 8.90 | 0.97 | 8.90 |
| The thermal resistance of the i -th layer, R_i (m ² K/W) | 0.062 | 6.08 | 0.062 |
| An indicator of the thermal inertia of the i -th layer D_i by the formula (5) | 0.55 | 5.92 | 0.55 |

Table 5.
Thermophysical and physical-mechanical characteristics of the wall layers (type “E”)

| Thermophysical and physical-mechanical characteristics of the wall layers* | Constructive wall layer starting from the inside of the room | | |
|---|--|----------------------------|--|
| | Inside lime – sandy plaster+ chocks of wood | Insulation – chopped straw | Outside lime – sandy plaster+ chocks of wood |
| The specific heat capacity of the material of the layer, c_i (J/kg×K) [22] | 2146.67 | 1675.00 | 2146.67 |
| The thickness of the layer, δ_i (m) | 0.10 | 0.30 | 0.10 |
| Density of the layer ρ_i , (kg/m ³) [22] | 866.67 | 200.00 | 866.67 |
| The weight of 1m ² wall, kg | 86.67 | 60.00 | 86.67 |
| The thermal conductivity of the layer λ_i , (W/mK) [22, 24, 25] | 0.71 | 0.08 | 0.71 |
| The coefficient of heat absorption of the i -th layer S_i (W/m ² K) [23] | 9.80 | 1.35 | 9.80 |
| The thermal resistance of the i -th layer, R_i (m ² K/W) | 0.14 | 4.00 | 0.14 |
| An indicator of the thermal inertia of the i -th layer D_i by the formula (5) | 1.38 | 5.41 | 1.38 |

* – 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.

always multilayered:

$$\tau_u = \pi^{-2} c \rho \delta R, \quad (1)$$

where c – specific heat capacity of the wall material, J/kgK;

ρ – the density of the material of the layers of the enclosing structures of walls, kg/m³;

$R = \frac{\delta}{\lambda}$ the thermal resistance of the wall, m²K/W;

δ – the thickness of the layer of the enclosing structure of the wall, m;

λ – thermal conductivity of the envelope material, W/mK.

Therefore, for numerical simulation of the thermal inertia time of various variants of envelopes, an analytical dependence for multilayered walls is used [26]:

$$\tau_u = \tau_u' L_n, \quad (2)$$

where τ_u' – the time of thermal inertia of a homogeneous wall of thickness δ with parameters of the first layer, which is determined by the dependence [26]:

$$\tau_u' = c_i \rho_i \delta^2 / \pi^2 \lambda_i, \quad (3)$$

L_n – layering factor of the envelope which is calculated by the formula [26]:

$$L_n = \left\{ 3 \delta_{tot} \delta_1^2 - 2 \delta_1^3 + \frac{\lambda_1}{c_1 \rho_1} \sum_{i=2}^n c_i \rho_i \delta_i^2 \left[\frac{\Delta \delta_i}{\lambda_i} + (1 + 2 \frac{\Delta \delta_i}{\delta_i}) \left(3 \sum_{j=1}^{i-1} \frac{\delta_j}{\lambda_j} + \frac{\delta_i}{\lambda_i} \right) \right] \right\} \delta_{tot}^{-3}, \quad (4)$$

where δ_{tot} – general thickness of multilayered envelope, m;

δ_1 – the thickness of the first layer of a multilayered envelope, 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.

To compare the thermal inertia of walls from different structural elements, the unbiased parameter of thermal inertia D [23] was determined

$$\sum_{i=1}^n D_i = \sum (S_i \cdot R_i), \quad (5)$$

Where $S_i = \sqrt{\frac{2\pi\lambda_i c_i \rho_i}{T}}$ – the coefficient of heat absorption W/m²K, of i -th layer of the envelope, [23];

T – a period of thermal oscillations, sec.

To determine the thermal inertia D , the daily period of thermal oscillations is assumed, i.e.

$$T = 24 \cdot 3600 = 86400 \text{ sec.}$$

Table 6.
Parameters of the considered multilayered envelopes

| Thermophysical and physical-mechanical parameters of the considered multilayered envelopes | Wall type | | | | |
|--|-----------|----------|----------|----------|----------|
| | Wall "A" | Wall "B" | Wall "C" | Wall "D" | Wall "E" |
| Thermal inertia of the base layer τ_{it}' , hours by the formula (3) | 11.67 | 11.67 | 11.44 | 11.67 | 18.44 |
| Layering coefficient of multilayered wall, L_n by the formula (4) | 9.11 | 1.61 | 1.68 | 1.03 | 1.62 |
| The total thermal inertia of multilayered wall τ_{it} , hours by the formula (2) | 106.32 | 18.77 | 19.22 | 11.98 | 29.85 |
| The sum of thermal resistances of the wall materials R , (m^2K/W) | 6.06 | 1.12 | 6.20 | 0.50 | 4.40 |
| Internal surface resistance R_{si} (m^2K/W) for horizontal heatflow [27] | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| External surface resistance R_{se} (m^2K/W) for horizontal heatflow [27] | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| The total R -value of the multilayered wall, (m^2K/W) | 6.23 | 1.29 | 6.37 | 0.67 | 4.57 |
| The total thermal transmittance of the multilayered wall $U=1/R$ -value, (W/m^2K) | 0.16 | 0.77 | 0.16 | 1.48 | 0.22 |
| An indicator of the thermal inertia of the wall, $\Sigma D_i=\Sigma(S_iR_i)$ | 16.31 | 7.08 | 7.02 | 5.41 | 8.69 |
| Pressure on the foundation p , kg/m | 655.00 | 1440.00 | 418.99 | 1920.00 | 466.67 |

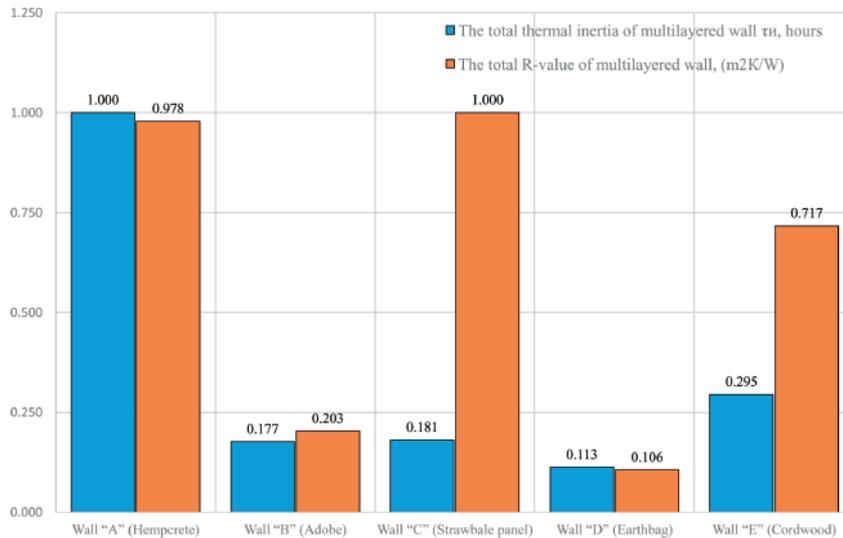


Figure 3.
Comparison of the normalized R-value and the total thermal inertia τ_{it} of the multilayered wall

5. RESULTS OF THE NUMERICAL MODELING OF THE THERMAL POTENTIAL OF THE WALLS FROM NATURAL MATERIALS OF ORGANIC ORIGIN

Table 6 gives calculations of the thermophysical (the total R -value, m^2K/W of multilayered construction, a non-dimensional value of the thermal inertia D , the thermal inertia of the base layer τ_{it} , duration of the quasi-stationary heat process τ_{it}' hours, non-dimensional layering coefficient of multilayered envelope L_n) and the physical-mechanical parameters (the spe-

cific pressure p_i on the foundation at the location of $1 m^2$ of the designed wall type kg/m).

It could be useful to make a comparison of the normalized values of the total R -value of the multilayered construction and the total thermal inertia τ_{it} of the multilayered construction, which is presented in Fig. 3. From Fig. 3 it could be seen that a hempcrete wall is the best one from the considered types of the walls in terms of R -value of the multilayered construction and the total thermal inertia of the multilayered construction τ_{it} with almost the highest values (1.000 and 0.978 for the total τ_{it} and the total R -value respective-

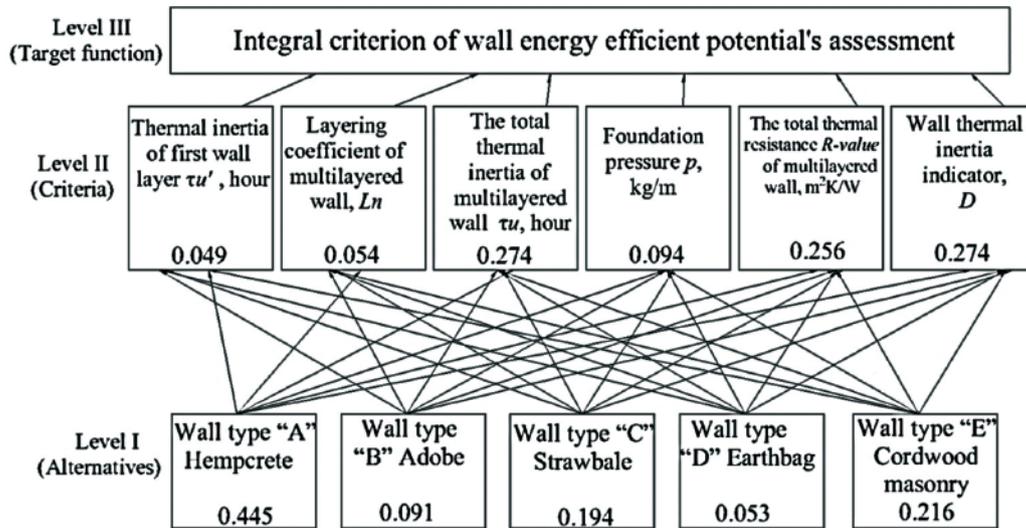


Figure 4. AHP model for assessment of non-dimensional integral criterion of energy efficiency potential

ly). Alongside with a hemcrete wall, a strawbale panel wall has the highest thermal resistance value, but it has almost five times smaller value of the total thermal inertia time (1.000 and 0.181 respectively). Walls "B", "D" have almost the same values of both parameters. The wall type "E" has also a big difference between the compared parameters (0.717 for the total R -value and 0.295 for the total τu).

Nevertheless, for the more objective, multi-criteria evaluation of the parameters of each of the investigated variants of the envelopes installation, the method of the Analytical Hierarchy Process, AHP [28] is used, as well as the methods proposed by the authors for determining the integral criterion of energy efficiency potential. Due to the fact, that during the assessment of the energy efficiency potential of the specific envelope of organic materials the influence of thermophysical parameters (R -value, coefficient of heat absorption S , thermal inertia D , thermal conductivity λ , specific heat capacity of material c) and physical-mechanical parameters (density ρ , mass m , thickness of layer δ) which were analysed have different dimensions, it is necessary to use a non-dimensional integral criterion for energy efficiency potential assessment of the multilayered envelopes.

It should be noted, that both methods for multi-criteria evaluation (based on AHP and proposed by authors) of the considered envelopes use one-scale non-dimensional units, which allow comparing their energy-efficient potential more objectively.

The integral criterion for energy efficiency potential assessment of the multilayered envelope of buildings is the normalized ratio of the total indicator of the energy efficiency potential of the specific envelope to the sum of values of the total indicators of the energy efficiency potential of the whole envelopes.

The use of such method of comparison as AHP allows us to apply a multicriteria assessment to choose a proper type of walls enclosing in terms of their multi-dimensional thermophysical and physical-mechanical characteristics.

According to AHP [28] a three-level hierarchy (model), has been built to determine the integral criterion for energy efficiency potential. This model represents the influence of the thermophysical and physical-mechanical characteristics of natural materials of organic origin on the target function (integral criterion of wall energy efficient potential's assessment) that can be described as the quantitative integral presentation of the indicator that takes into account the influence of different parameters by its nature (Fig. 4). Numbers presented on Fig. 4 show an influence of factor's weights (Level II, in the bottom part of each criteria rectangle) and numerical assessment of each alternative (Level I, in the bottom part of each wall type rectangle).

The methodology of creating a hierarchical model for determining the integral criterion of energy efficiency potential assessment for envelopes from organic materials is listed below.

Table 7.
Matrix of pairwise comparing for criteria (Level II of Fig. 4)

| Comparison Criteria | The thermal inertia of the base layer $\tau u'$, hour by the formula (3) | Layering coefficient of multilayered wall L_n , by the formula (4) | The total thermal inertia of multilayered wall τu , hour by the formula (2) | Foundation pressure p , kg/m | The total R -value of multilayered wall, m^2K/W | Wall thermal inertia indicator, $\Sigma D_i = \Sigma (S_i R_i)$ | The vector of weights by the formula (7) | The normalized weight of the criterion |
|---|---|--|---|--------------------------------|---|---|--|--|
| The thermal inertia of the base layer $\tau u'$, hour by the formula (3) | 1 | 1 | 1/6 | 1/2 | 1/5 | 1/6 | 0.375 | 0.049 |
| Layering coefficient of multilayered wall L_n , by the formula (4) | 1 | 1 | 1/5 | 1/2 | 1/4 | 1/5 | 0.414 | 0.054 |
| The total thermal inertia of multilayered wall τu , hour by the formula (2) | 6 | 5 | 1 | 3 | 1 | 1 | 2.117 | 0.274 |
| Foundation pressure p , kg/m | 2 | 2 | 1/3 | 1 | 1/3 | 1/3 | 0.727 | 0.094 |
| The total R -value of multilayered wall, m^2K/W | 5 | 4 | 1 | 3 | 1 | 1 | 1.979 | 0.256 |
| Wall thermal inertia indicator, $\Sigma D_i = \Sigma (S_i R_i)$ | 6 | 5 | 1 | 3 | 1 | 1 | 2.117 | 0.274 |

By pairwise comparing [28] the priority of each of the criteria (the thermal inertia of the first layer $\tau u'$, layering factor of the envelope L_n , the total thermal inertia time of multilayered wall τu , the total R -value of multilayered wall, the dimensionless index of wall thermal inertia D and pressure p on the foundation) has been weighted for each of the alternative wall types. The weight of each criteria (local priorities, Level II in Fig. 4) shows how much the influence factor contributes to the goal (Level III, target function in Fig. 4). The global priorities (Level I) show how much each wall type weighs in terms of the energy efficiency potential.

Each of the abovementioned local priorities is a matrix [27, 28], which is filled in the following way,

$$A = \begin{bmatrix} 1 & \frac{r_1}{r_2} & \frac{r_1}{r_3} & \dots & \frac{r_1}{r_n} \\ \frac{r_2}{r_1} & 1 & \frac{r_2}{r_3} & \dots & \frac{r_2}{r_n} \\ \dots & \dots & \dots & \dots & \dots \\ \frac{r_n}{r_1} & \frac{r_n}{r_2} & \frac{r_n}{r_3} & \dots & 1 \end{bmatrix}, \quad (6)$$

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 the investigated parameters (thermal resistance R , heat absorption coefficient S , unbiased parameter of heat inertia D , thermal conductivity λ , specific heat capacity of the wall material c , density ρ , mass g , layer thickness δ).

Knowing the line elements of the matrix (6), elements of all other lines are calculated. The arbitrary element $a_{ij} = r_i / r_j$, with known elements $a_{kj} = r_k / r_j$, k , and $i = \overline{1, n}$ of a certain n -th line, is calculated as $a_{ij} = a_{kj} / a_{ki}$, and, $j, k = \overline{1, n}$.

The advantage vector of each i -th parameter is m_i calculated as the average geometric value of the elements of each matrix line divided by the sum of all the average geometric values for the estimated parameters using the formula [28]

$$\sqrt[n]{1 \times \frac{r_1}{r_2} \times \frac{r_1}{r_3} \times \dots \times \frac{r_1}{r_n}} = m_1. \quad (7)$$

Then, the advantage vector for the first line of the matrix which is obtained by the formula (6) is calculated, taking into account the average geometric elements of each of the lines using the formula

$$\frac{m_1}{m_1 + m_2 + \dots + m_n} = x_1, \quad (8)$$

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

Table 8.
Eigen vector η_{\max} , consistency index CI , consistency ratio CR for matrix (Level II)

| | |
|--|-------|
| Characteristic number of the vector, η_{\max} | 6.013 |
| Consistency index, CI | 0.064 |
| Consistency ratio, CR | 0.052 |

By analogy, the components of the eigen vector and the advantage vector for other m_n lines are determined.

As the set of the relative weights of the alternatives, we use the components of our eigen vector that corresponds to the maximal characteristic number η_{\max} [28]. Moreover, in order to evaluate the coherence of the matrix, the condition $\eta_{\max} \geq n$ must be fulfilled.

As an indicator of the degree of the consistency in the elements of matrix A , the consistency index (CI) is used [28]

$$CI = (\eta_{\max} - n) / n - 1, \quad (9)$$

where n is the rank of the matrix.

To assess the adequacy of the consistency degree, the consistency ratio (CR) is used which is equal to

$$CR = CI / MRCI, \quad (10)$$

where $MRCI$ is an average random consistency index, the average value which is randomly calculated for a large number of pair comparisons matrices that were generated on the fundamental scale [28].

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

Tables 7, 8 give the meanings and fillings of all the components of the matrix – its eigen vector η_{\max} , the consistency index CI of the pair of comparisons, as well as the consistency ratio CR for the “Criteria” matrix.

In this matrix (Table 7), in each cell, expert assessments of the benefits of one of the factor of influence over the other has been evaluated by the most common 9-point Saati scale [28]. At the same time, the filling of the matrix (Table 7) is carried out according to the rule: the number of more than one unit is put in a cell if the evaluated parameter on the left has an advantage over the parameter above it on the desired criterion. 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. After that, each local vector of the advantages (weight) of each of the influencing factors (level II) is multiplied by the global vector of alternatives advantage. All the weights of the vectors of advantages for the remaining matrices and factors of influence have been found on the given algorithm.

To determine the integral criterion of wall energy efficient potential of the envelope (Level III), the product of each of the identified alternative vectors is summed by the weight of each criterion (Table 7). This allows to quantify the energy efficient potential of each type of the envelope.

The method proposed by the authors for determining the integral criterion of the energy efficiency potential of the envelope is as follows:

1. Normalized indicators with different units of measurement are determined by the formula

$$n_{norm,j} = \frac{n_j}{n_{max,j}}, \quad (11)$$

where n_j – the value of the j -th comparison parameter (lines of the first column of table 6) obtained by the formulas (2) ... (5).

$n_{max,j}$ – the maximum value of the j -th comparison parameter for each j -th line of table 6 for different types of envelopes;

2. In order to take into account the negative quantitative influence of the pressure parameter on the foundation (the higher the pressure on the foundation, the lower the estimation of the parameter), the inverse of the normal value of the parameter of dependence on the formulas is calculated:

$$c_i = \frac{1}{n_{norm,i}} = \frac{n_{max,f}}{n_{fi}}, \quad (12)$$

$$d_i = \frac{c_i}{c_{max,f}} = \frac{n_{max,f}}{n_{fi} \cdot c_{max,f}}, \quad (13)$$

where $n_{max,f}$ – the maximum value of the parameter “Pressure on the foundation p ” of the five considered walls;

n_{fi} – pressure on the foundation for the i -th version of the wall arrangement;

$c_{max,f}$ – the maximum value of the parameter “Pressure on the foundation p ”, converted to the normalized value, from the range of five different types of envelopes;

Table 9.
Criteria of energy efficiency potential of envelopes and target function

| A variant of the wall fence | Criteria for evaluation | | | | | | The total value of the integral criterion for energy efficiency assessment |
|-----------------------------|---|--|---|--------------------------------|--|---|--|
| | The thermal inertia of the base layer $\tau u'$, hour by the formula (3) | Layering coefficient of multilayered wall L_n , by the formula (4) | The total thermal inertia of multilayered wall τu , hour by the formula (2) | Foundation pressure p , kg/m | The total R-value of multilayered wall, m^2K/W | Wall thermal inertia indicator, D , $\Sigma D_i = \Sigma (S_j R_i)$ | |
| Wall "A" | 0.007 | 0.033 | 0.151 | 0.018 | 0.091 | 0.146 | 0.445 |
| Wall "B" | 0.007 | 0.006 | 0.027 | 0.006 | 0.016 | 0.029 | 0.091 |
| Wall "C" | 0.007 | 0.006 | 0.027 | 0.035 | 0.091 | 0.029 | 0.194 |
| Wall "D" | 0.008 | 0.003 | 0.014 | 0.004 | 0.009 | 0.016 | 0.053 |
| Wall "E" | 0.020 | 0.006 | 0.056 | 0.032 | 0.050 | 0.053 | 0.216 |

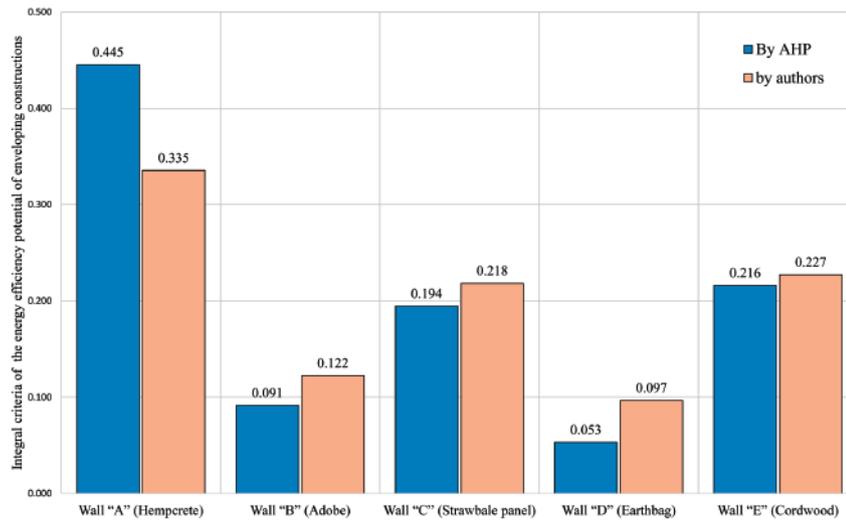


Figure 5.
Values of the integral criterion of the energy efficiency potential of envelopes by different methods

3. The integral criterion of the energy efficiency potential of the i -th type of envelope is defined as the value of the formula

$$I_{n,i} = \frac{\sum_{j=1}^5 n_{norm,j} + d_i}{\sum_{j=1}^5 (n_{norm,j} + d_i)}, \quad (14)$$

where $\sum_{j=1}^5 n_{norm,j} + d_i$ – the total sum of j parameters including the i -th foundation pressure of energy efficiency potential’s criterion of the i -th envelope type;
 $\sum_{j=1}^5 (n_{norm,j} + d_i)$ – the total sum of the energy efficiency potential’s criteria of whole types of “A” ... “E” envelopes.

Criteria for calculating the energy efficiency poten-

tial of the envelopes from natural materials of organic origin and the target function calculated by the AHP [28] are given in Table 9.

The criteria of the energy efficiency potential assessment by the authorship method, which are calculated by formulas (11) ... (14) are presented in Table 10.

The graphical comparison of the values of the integral criterion for the energy efficiency potential assessment of different envelope types using the two methods is presented in Fig. 5.

On the basis of the analysis of the bar chart graph in Fig. 5, we can conclude that the best wall type is still the hemprete one with the highest values of the integral criterion of the energy efficiency potential, according to both methods. The assessment of different envelopes presents almost the same disposal for all types of walls (except the earthhbag wall with almost twice higher value by authors’ method from AHP method (0.097 and 0.053 respectively).

Table 10.
Integral criteria for assessing the energy efficiency potential by authorship methodology

| Criteria for evaluation | A variant of the wall fence | | | | |
|--|-----------------------------|----------|----------|----------|----------|
| | Wall "A" | Wall "B" | Wall "C" | Wall "D" | Wall "E" |
| The thermal inertia of the base layer τ_u' , hour by the formula (3) | 0.633 | 0.633 | 0.621 | 0.633 | 1.000 |
| Layering coefficient of multilayered wall L_n , by the formula (4) | 1.000 | 0.177 | 0.184 | 0.113 | 0.178 |
| The total thermal inertia of multilayered wall τ_u , hour by the formula (2) | 1.000 | 0.177 | 0.181 | 0.113 | 0.281 |
| Foundation pressure p , kg/m | 0.341 | 0.750 | 0.218 | 1.000 | 0.243 |
| The total R -value of multilayered wall | 0.978 | 0.203 | 1.000 | 0.106 | 0.699 |
| Wall thermal inertia indicator D , $\Sigma D_i = \Sigma (S_i R_i)$ | 1.000 | 0.434 | 0.431 | 0.331 | 0.501 |
| Returns to the normalized value of the criterion c_i by the formula (12) | 2.931 | 1.333 | 4.582 | 1.000 | 4.114 |
| Influence of the negative foundation pressure parameter d_i by the formula (13) | 0.640 | 0.291 | 1.000 | 0.218 | 0.898 |
| Value of the integral criterion for assessing the energy efficiency potential of the i -th version of the envelope $I_{n,i}$, by the formula (14) | 0.335 | 0.122 | 0.218 | 0.097 | 0.227 |

6. DISCUSSION OF THE RESULTS OF THE STUDY

The cordwood wall has the very similar values of the integral criterion of energy efficiency potential assessment of envelopes by different calculated methods (0.216 and 0.227 by AHP and authorship respectively), the largest difference, approximately twice as much, is observed in the earthbags wall, with 0.053 by AHP and 0.097, according to the authors' method. It could be said that the divergence of the criteria's values of the energy efficiency potential calculated by the AHP in comparison with the author's technique is related to the subjective evaluation of the advantages of one comparison criterion over another.

From Fig. 5 it can be concluded that the hempcrete envelope is the most effective wall type (coefficient of 0.445 for AHP and 0.335 for authors), the strawbale panels wall and cordwood one can also be acceptable from the standpoint of the energy efficiency potential criterion. They have respectively 0.216 for AHP and 0.227 by the authors for the cordwood wall, and 0.194 and 0.218 for the wall made of strawbale panels.

Obviously, the obtained values of the integral criterion of energy efficiency potential which were determined by different methods can not be considered fully completed, because they do not reflect additional, necessary to the authors' opinion, data for analysis – climate factor, the lifetime of the wall construction (or of the building) without overhaul and the cost of the wall type installation. Due to the lack of this additional data, the optimal choice of the wall type is still an ambiguous challenge.

However, if we compare the envelope types not only

in the context of thermophysical and physical-mechanical characteristics but also in the context of an economic factor (the cost of materials and work during the installation), an environmental factor (primary energy consumption for materials production, transportation and installation), a climate factor, a durability factor (lifetime period of construction), the assessment of the energy efficiency potential will be more objective and complete. Thus, it is necessary to recognize the additional criteria for a more objective comparison and choice for the best option of wall types.

7. CONCLUSIONS

1. The time of thermal inertia of the multilayered envelopes, as one of the thermophysical indicators of wall materials, is one of the criteria of a building's energy efficiency, which indirectly allows to estimate the costs of a comfortable stay of a person in a building with a given wall construction.
2. The analytically determined time of thermal inertia for different types of envelopes from natural materials of organic origin has shown that the best construction envelope with a fixed width of 0.5 m is a hempcrete wall with 106 hours, the worst one is an earthbag wall with almost 12 hours.
3. A multicriteria assessment of the energy efficiency potential of different types for the erecting of enclosing structures from organic origin makes it possible to select the envelope type more objectively.
4. The hempcrete wall is the most effective in terms of the proposed criterion of energy efficiency assessment (0.445 for the AHP and 0.335 for the

authors), the strawbale panels wall type and the cordwood wall can also be acceptable (an estimate of 0.216 for AHP and 0.227 for the authors for the cordwood wall type and 0.194 and 0.218 for the strawbale panels wall).

5. It is obvious that for the more objective assessment of the energy efficiency potential of a specific type of envelope, it is necessary to consider not only the thermophysical and physical-mechanical characteristics but also an economic factor (the cost of materials and work during the installation), an environmental factor (primary energy consumption for materials production, transportation and installation), a climate factor, a durability factor (lifetime period of construction), etc.

REFERENCES

- [1] Sychev, S. A. (2014). Ekotekhnologii stroitelstva s uchetom kriteriyev energoeffektivnykh zdaniy (Ecotechnologies of construction by taking into account criteria of energy efficient buildings). *Science Time*, 10, 343–349 (in Russian).
- [2] Brojan, L., Petric, A., Clouston, P. L. (2013). A comparative study of brick and strawbale wall systems from environmental, economical and energy perspectives. *ARPJ Journal of Engineering and Applied Sciences*, 8, 920–926.
- [3] Ukrainian National Standard. DSTU-N B.V. 2.2-13: 2015. (2015). Energy performance of building. Guidance on the application of energy assessment of buildings. Kyiv, Ukraine: Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine, (in Ukrainian).
- [4] Lapin, Y. N. (2005). Avtonomnyye ekologicheskiye doma (Autonomous ecological houses). Moskva: Algoritm (Moscow: Algorithm), (in Russian).
- [5] Bläsi, W. (2001). Bauphysik. Bibliothek des technischen Wissens. 3 Auflage. (Building physics. Library of technical knowledge. 3 Edition). Haan: Verlag Europa Lehrmittel.
- [6] Osobennosti maloetazhnogo energoeffektivnogo ekologicheskogo stroitelstva v raznykh klima-ticheskikh zonakh (Features of low-rise energy-efficient ecological construction in different climatic zones). Retrieved from http://www.itp.nsc.ru/conferences/mzhz_2017/files/Section_02.pdf#page=16 (in Russian)
- [7] Galkin, P. I. (1944). Ognestoykiye glinyanye stroitelnyye materialy (Fire-resistant clay building materials). Moskva – Leningrad: Akademiya kom. khoz-va im. K. D. Pamfilova (Moscow – Leningrad: Academy of Communal Households named after KD Pamfilov), (in Russian).
- [8] Nanazashvili, I. K. (1990). Stroitelnyye materialy iz drevesno-tsementnoy kompozitsii (Building materials from wood-cement composition). Leningrad: Stroyizdat, (in Russian).
- [9] Lobanova, A. V., Kazimagomedov, I. E. (2015). Stenovyye izdeliya iz arbolita na osnove kostry lna (Wood concrete on the base of fiber flax for wall details). *Komunalnoye khozyaistvo gorodov (Municipal economy of cities)*, 124, 18–20, (in Russian).
- [10] Shea, A., Lawrence, M., & Walker, P. (2012). Hygrothermal performance of an experimental hemp–lime building. *Construction and Building Materials*, 36, 270–275.
- [11] Pacheco-Torgal, F., Jalali, S. (2012). Earth construction: Lessons from the past for future eco-efficient construction. *Construction and Building Materials*, 29, 512–519.
- [12] Rajesh Kumar, J. (2013). A study on eco friendly cost effective earthbag house construction. *Kathmandu University Journal of Science, Engineering and Technology*, 9(1), 200-211.
- [13] Kulichenko, I. I. (2013). Ekonomichna efektyvnist vykorystannia mistsevykh ekolohichnykh materialiv v malopoverkhovomu budivnytstvi dostupnoho zhytla (Economic efficiency of using local environmental materials in low-rise construction of affordable housing). *Stroytelstvo. Materyalovedenye. Mashynostroenye. Seryia: Innovatsyonnye tekhnolohyy zhyznennoho tsykla obiectov zhylyshchno-hrazhdansko-ho, promyshlennoho i transportnoho naznachenyya (Construction. Material science. Mechanical engineering. Series: Innovative technologies of the life cycle of object)*, 69, 257–264, (in Ukrainian).
- [14] Biks, Y. S. (2017). Perspektivy vykorystannia vyrobiv z solomy u malopoverkhovomu budivnytstvi. (Perspectives for the use of straw products in low-rise building). *Suchasni tekhnolohii, materialy i konstruktsii u budivnytstvi (Modern technology, materials and design in construction)*, 22(1), 75-83 (in Ukrainian).
- [15] Geokar – nedorogoy i dostupnyy stroitelnyy material (Geokar – inexpensive and affordable building material). Retrieved from http://found.com.ua/news/wall_up_covering_flor/building_materials/геокар%20недорогой%20и%20доступный%20строительный%20материал.html (in Russian).
- [16] Sheina, S. G., Minenko, E. N. (2012). Razrabotka algoritma vybora energoeffektivnykh resheniy v stroitelstve (Development of complex energy efficient measurements' choice algorithm in construction processes). *Inzhenernyy vestnik Dona (Don Engineering herald)*, 22(4-1), 133-136, (in Russian).
- [17] Matsura, A. A., Ermolenko, B. Y. (2015). Razrabotka metodov optimalnogo proyektirovaniya energoeffektivnykh domov (Development of methods for the optimal design of energy-efficient homes). *Uspekhi*

- v khimii i khimicheskoy tekhnologii (Advances in chemistry and chemical technology), XXIX(8), 118–122, (in Russian).
- [18] Smirnova, S. N. (2009). . Teoreticheskaya model energoeffektivnogo zdaniya (Theoretical model of an energy efficient building). *Privolzhskiy nauchnyy zhurnal. Seriya: Arkhitektura. Dizayn (Volga scientific journal. Series: Architecture. Design)*, 2, 86–91, (in Russian).
- [19] Savitsky, M. V., Babenko, M. M. (2014). Pokaznyky enerhoefektyvnosti ekolohichnoho malopoverkhovoho budynku z mistsevykh materialiv (Indicators of energy efficiency of an ecological low-rise building of local materials). *Stroytelstvo. Materyalovedenye. Mashynostroenye. Seriya: Innovatsyonne tekhnolohy zhyznennoho tsykla ob'ektov zhylyshchno-hrazhdanskoho, promyshlennoho i transportnoho naznacheniya (Construction. Material science. Mechanical engineering. Series: Innovative technologies of life cycle of objects of housing and civil, industrial and transport purposes)*, 77, 168–172, (in Ukrainian).
- [20] Stazi, F. (2017). *Thermal Inertia in Energy Efficient Building Envelopes*. Butterworth-Heinemann.
- [21] Clarke, J. A., Yaneske, P. P., Pinney, A. A. The Harmonisation of Thermal Properties of Building Materials. Retrieved from http://www.esru.strath.ac.uk/Documents/89/thermop_rep.pdf.
- [22] Ukrainian National Standard. DSTU B.V. 2.6-189: 2013. (2014). *Methods of choosing insulation material for insulation of buildings*. Kyiv, Ukraine: Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine, (in Ukrainian).
- [23] Filonenko, O. I., Yurin, O. I. (2015). *Budivelna a teplofizyka ohorodzhualnykh konstruksii budivel: navch. posibnyk (Construction and Thermal Physics of Building Enclosures: A manual)*. Poltava: Poltavskiy natsionalnyi tekhnichnyi universytet im. Yuriiia Kondratiuka (Poltava: Poltava National Technical University named after Yuri Kondratyuk), (in Ukrainian). Ukrainian National Standard. DSTU-N B.V. 2.6-190: 2013. (2014). *Manual on the estimation of design parameters of heat absorption and heat resistance of walling*. Kyiv, Ukraine: Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine, (in Ukrainian).
- [24] Ezennia, I. S., Alibaba, H. (2017). A Systematic Review Of Thermal And Moisture Performance Of Straw-Bale Houses In Hot And Humid Climates. *International Journal of Scientific & Technology Research*, 6(1), 13–18.
- [25] Arumi-Noe, F., Hamilton, K. (2013). Thermal inertia of Straw bale walls. Buildings XII Conference, Florida, USA. Retrieved from http://web.or.nl.gov/sci/buildings/2012/1998%20B7%20papers/063_Arumi_No_e.pdf (Diciembre, 2015). Benfratello, S., Capitano, C., Peri, G., Rizzo, G., Scaccianoce, G., Sorrentino, G. (2013). *Thermal and structural properties of a hemp–lime biocomposite*. *Construction and Building Materials*, 48, 745–754.
- [26] Korshunov, O., Zuev, V. (2011). Vremya teplovy inertsii termicheskoye soprotivleniye sloistykh sten (Time of thermal inertia and thermal resistance of multilayered walls). *Energoresursosberezheniye i energoeffektivnost (Energy saving and energy efficiency)*, 4(40), 23–26, (in Russian).
- [27] Ukrainian National Standard. DSTU ISO 6946: 2007. (2007). *Building components and building elements. Thermal resistance and thermal transmittance. Calculation methods*. Kyiv, Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine, (in Ukrainian).
- [28] Saaty, T. L. (2009). (Prinyatiye resheniy pri zavisimostyakh i obratnikh svyazyakh: Analiticheskiye seti: per. s angl) (Decision-making with dependencies and inverse connections: Analytical networks: Translated from English. Moscow: LIBROCOM Book House, (in Russian).