A R C H I T E C T U R E   C I V I L   E N G I N E E R I N G   E N V I R O N M E N T
The Silesian University of Technology   No. 1/2021

doi: 10.21307/ACEE-2021-006

ENERGY EFFICIENCY ASSESSMENT OF HEAT INSULATION BUILDING PRODUCTS: FUZZY-PROBABILISTIC APPROACH

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Received: 11.10.2019; Revised: 3.01.2021; Accepted: 8.01.2021

Abstract
The expediency of using heat-insulating construction products from a straw at the erecting of energy-efficient envelope constructions is considered in the paper. The hierarchical model in the form of an inference tree of the factors influencing the target function – reliability of energy efficiency of heat-insulating building products made of straw has resulted. A fuzzy matrix of knowledge is proposed which reflects the influence of thermophysical, physic-mechanical and durability parameters on the target function. The hierarchical connections between classified factors proceeded by apparatus of fuzzy logic and linguistic variables. A system of fuzzy logical equations which describes linguistic expressions of input variables according to the corresponding terms is proposed. In the research the expressions which describe the objective function – reliability of energy efficiency of heat-insulating construction products made of straw were obtained. It was made with the of membership functions following linguistic variables, by taking into account both qualitative as well as quantitative factors of influence. Represented in the paper model can be used as the design and engineering tool for the prediction of thermal performance of any multilayered wall assembly at the design stage of the project to assess complex energy efficiency parameters, which could be applied in practice during the decision-making process.

Keywords: **Modelling; Reliability; Energy efficiency; Thermal insulation; Linguistic variable; Fuzzy logic; Construction product.**

1. INTRODUCTION

The concept of “energy efficiency” has many interpretations, but if to express the most typical, it obviously will be the degree or measure of efficient use of any energy resource that is brought to the object that is the consumer of these resources.

One of the quantitative definitions of energy efficiency of a building can be the Energy conversion efficiency, $\eta = E_{useful\ output} / E_{input}$ which is expressed by the ratio of useful work $E_{useful\ output}$, expressed in units of energy to the work brought to the house E_{input}, expressed in units of energy.

According to the authors of the review [1], energy efficiency involves the elimination of unnecessary energy waste and increases its efficiency in all energy processes that take place in the house.

The maximum energy efficiency will have those buildings in which at the same rate of the energy conversion efficiency, the amount of total investment in the installation of thermal insulation and engineering systems to ensure optimal indoor climate will have a minimum value at their maximum durability. Significant energy consumption to maintain the thermal comfort of the premises does not increase the energy efficiency of buildings.

In modern scientific research solving, the problem of decision-making in uncertainty conditions where the choice of alternatives requires the analysis of complex information of different physical nature in search of the best solution is called a methodology of systems analysis. The essence of system analysis is multicriteria (decision) analysis (MCDA). That is why, when designing energy-efficient buildings, there is a need for a systematic analysis of the factors that affect the multicriteria (as usual) value of the objective function. With the help of system analysis, it is possible to substantiate the optimal design solution to reduce energy costs for the construction and operation of the building as a single energy and environmental system.

The concept of “reliability” is used very often in various branches of technics. In the material of this paper, the authors consider the term “reliability” as an integral indicator that numerically expresses the probability of providing several guaranteed thermophysical, physic-mechanical and durability characteristics in the design of thermal insulation products.

The author [2] believes that the urgency of the problem of ensuring the reliability of technical facilities, including buildings, structures and building structures is obvious because no one needs unreliable equipment, structures, materials, failure of which can lead to material and social losses.

Ensuring the reliability of the thermal insulation shell guarantees the maintenance of optimal microclimatic conditions of the premises at the actual consumption of thermal energy for heating. When substantiating the need for construction of low-rise buildings using multilayered thermal insulation products made of straw, there is a need to assess the reliability of their energy efficiency, by taking into account both quantitative and qualitative parameters of impact.

2. LITERARY ANALYSIS AND RESEARCH PROBLEM STATEMENT

The scarcity of fossil energy reserves, especially oil, natural gas and coal, leads to a significant increase in their value. This requires the implementation of advanced up to dated technologies aimed at reducing energy consumption to ensure the affordable thermal regime of buildings [3].

The authors of the study [4] have confirmed that increasing the energy efficiency of buildings is impossible without improving the thermal insulation capacity of envelopes. The authors propose a method of modelling the mechanism of energy-saving management in substantiating the choice of ecological and economic feasibility of materials for thermal modernization of the thermal insulation of buildings.

The materials are recommended for the installation of thermal insulation shell by the Ukrainian Code of thermal insulation [5], do not fully justify the decision-making in the design and technological implementation of multilayered opaque structures from presented in Code thermal insulation materials of organic origin, for instance as [6, 7, 8, 9, 10]. This is also confirmed by studies presented in [11, 12, 13].

In paper [14] the mathematical apparatus of probability theory was used to determine the variability probability of thermophysical parameters of enclosing structures. The variability of physic-mechanical characteristics of building materials in general [15], [16] and materials of natural origin in particular [8] presupposes the use of a probabilistic approach to determine their main thermal performance parameters. That is why in the paper [14] it is proposed to operate with such a concept as reliability. The authors of [14] proposed criterion of “thermal failure”. This criterion is numerically equal to the probability of moisture condensation on the inner surfaces of enclosing structures in the room, with a decrease in local temperatures of the inner surfaces of the insulating shell to the temperature of steam [14].

In the researches [11, 12, 17, 18], the methodological basis for ensuring energy efficiency of buildings and thermal reliability in terms of heat-accumulating ability [19, 20] of enclosing structures. A methodology for analyzing the energy efficiency of buildings taking into account the level of thermal comfort in the premises is also proposed.

3. PURPOSE AND TASKS OF THE RESEARCH

The conducted analysis of literature sources [22], [23] has shown that major reasons for the insignificant use of straw products as cheap value, natural and ecologically friendly by-product material, particularly in Ukraine, are the lack of practical experience in assessment of its real thermal performance characteristic, bias to the material in guaranteeing of the comfortable living conditions, etc.

There is also no methodology in Ukrainian Building Codes for assessment of their energy efficiency, during the erecting of the thermal insulation shell. All of the abovementioned encouraged the authors to dedicate the present research to the developing of a mathematical model for assessing the reliability of energy efficiency of thermal insulation construction products made of straw using a fuzzy knowledge base.

To do this, the authors propose to solve the following problems:

1. Construction of a hierarchical classification of quantitative and qualitative factors influencing the reliability of energy efficiency of thermal insulation building materials from straw using an expert fuzzy knowledge base.
2. Development of a mathematical model for complex assessment of the reliability of thermal insulation building materials made of straw, based on linguistic variables by fuzzy rules and fuzzy logical operations.

4. METHODS OF RESEARCH

In assessing the reliability the concept of the structural-probabilistic model was used [24]. This model requires a huge amount of statistical samples and reliable data about the distribution law of reliability indicators. To analyze the types, consequences and intensity of failures as an indicator of reliability the following methods could be applied [24, 25, 26]:

– uniform distribution of reliability;
– weights;
– indefinite Lagrange multipliers;
– matrix method of reliability calculation;
– Delphi method;
– method of statistical modelling, etc.

The reliability assessment method's selection is based on the following criteria: the object life cycle, the failure criteria, etc.

The reliability of the efficiency ensuring of the thermal insulation construction products can be determined by the probability of their complex parameters failure-free during the life cycle of the building by the formula [25]

$$R(t) = 1 - F(t), \tag{1}$$

where $R(t)$ – the probability of complex parameters of heat-insulating construction products failure-free state;

t – the time during which construction products could probably lose their regulatory parameters;

$F(t)$ – the probability of construction products loss their regulatory parameters,

Evaluation of the objective function – the reliability of energy efficiency of thermal insulation construction products from straw using equation (1) requires a significant database of experimental data. Besides, the objective function contains both quantitative and qualitative factors. One of the mathematical devices that allow operating with such data is the device of fuzzy logic [27].

According to this mathematical apparatus, the fuzzy set by which the term F is formalized is a set of parameters

$$F = \frac{\mu_F(u_1)}{u_1} + \frac{\mu_F(u_2)}{u_2} + \ldots + \frac{\mu_F(u_n)}{u_n}, \tag{2}$$

where $(u_1, u_2, \ldots, u_n)$ is a universal set U on which a fuzzy set $F \in U$ is given;

$\mu_F(u_i)$ is the degree to which the element $u_i \in U$ belongs to the fuzzy set F.

The logical conclusion between cause and effect is described by a system of fuzzy logical statements, respectively:

For the MIN operation

$$\mu_C(u) = \mu_A(u) \wedge \mu_B(u). \tag{3}$$

For the MAX operation

$$\mu_D(u) = \mu_A(u) \vee \mu_B(u). \quad (4)$$

Fuzzy logical operations *AND* (∧), *OR* (∨) are performed in compliance with the rules:

$$\mu_{A \wedge B}(u) = \min(\mu_A(u), \mu_B(u)). \quad (5)$$

$$\mu_{A \vee B}(u) = \max(\mu_A(u), \mu_B(u)). \quad (6)$$

The rule of distribution of belonging degrees according to the normalization ($\mu_1 + \mu_2 + \ldots \mu_n$) = 1 is given in the form of relationship as follows:

$$\frac{\mu_1}{r_1} = \frac{\mu_2}{r_2} = \ldots = \frac{\mu_n}{r_n}, \quad (7)$$

where $r_i = r_F(u_i) = u_i$ – the rank (number) which is characterized by the significance of this element in the formation of the property described by the fuzzy term *F*;

$\mu_i = \mu_F(u_i)$.

The degree of membership $\mu_F(u_i)$ of the element $u_i \in U$ to a fuzzy term is determined by relative estimates of the ranks $r_1 / r_j = a_{ij}$, $i, j = 1,\ldots, n$, which create a matrix:

$$A = \begin{bmatrix} 1 & \frac{r_2}{r_1} & \frac{r_3}{r_1} & \cdots & \frac{r_n}{r_1} \\ \frac{r_1}{r_2} & 1 & \frac{r_3}{r_2} & \cdots & \frac{r_n}{r_2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{r_1}{r_n} & \frac{r_2}{r_n} & \frac{r_3}{r_n} & \cdots & 1 \end{bmatrix} \quad (8)$$

By the known line elements of the matrix (8), elements of all other lines are calculated. The arbitrary element $a_{ij} = r_i / r_j$, with known elements $a_{kj} = r_k / r_j$, $k,i = \overline{1,n}$ of a certain n-th line, is calculated as

$a_{ij} = a_{kj} / a_{ki}$, $i, j, k, = \overline{1,n}$.

In this matrix (8), in each cell, expert assessments of the benefits of one of the factors of influence over the other have been evaluated by means of a 9-point Saati scale [28].

5. CALCULATION OF THE PROPOSED MODEL PARAMETERS

In the research [29] the hierarchical classification of quantitative as well as qualitative influence factors which characterizes the reliability of efficiency of heat-insulating building products from a straw for envelope multilayered designs has been proposed.

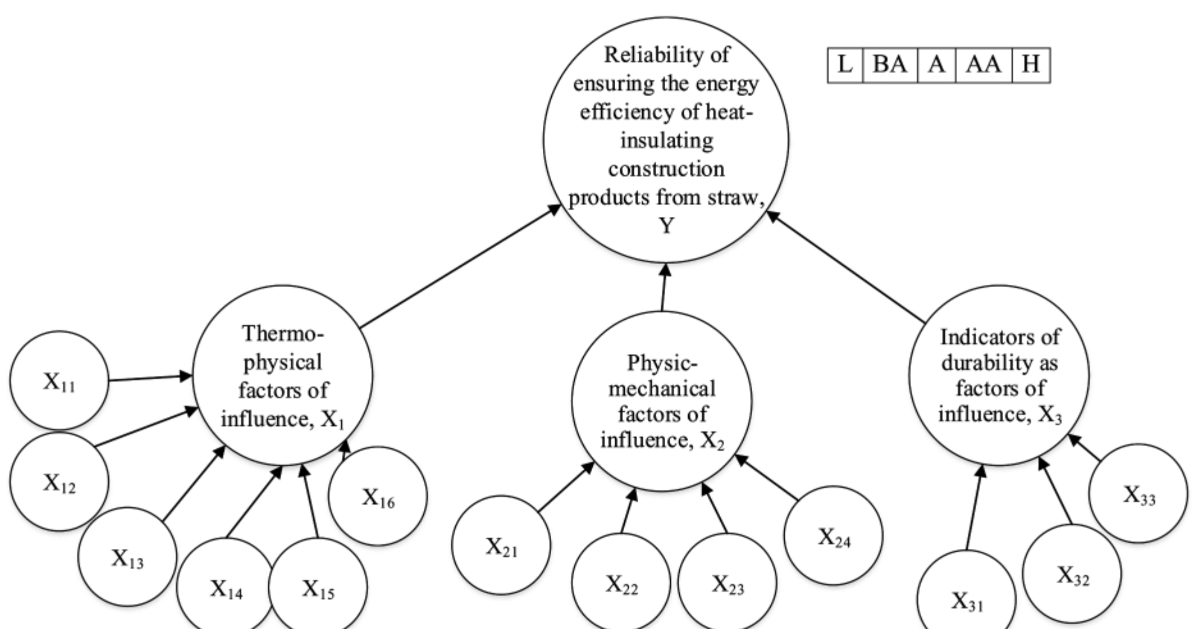

Figure 1.
Hierarchical model in form of the inference tree for assessment of the energy efficiency reliability of heat-insulating construction products from straw

Taking into account the results of research [29], Fig. 1 presents a structural model of hierarchical relationships in the form of a logical inference tree for linguistic variables that describe, thermo-physical, physic-mechanical and durability indicators as factors of influence respectively.

The root of the logical inference tree corresponds to the value of the objective function – the assessment of the reliability of energy efficiency of thermal insulation products made of straw, and hanging tops – quantitative and qualitative thermo-physical, physic-mechanical parameters as well durability indicators as linguistic variables, respectively.

According to the principle of linguistic variables, the causal relationships between the influencing factors of the model are described using fuzzy terms [4], [27]. The qualitative fuzzy term as a linguistic variable is defined by a word that characterizes the quantitative expressions “Low” (L), “Below average” (BA), “Average” (A), “Above average” (AA) and “High” (H). Proposed fuzzy terms create expert fuzzy knowledge bases that characterize the relationships between input and output variables.

Reliability of efficiency of heat-insulating building products from a straw for envelope designs according to researches [29] and the inference tree (Fig. 1) as linguistic variable Y, is presented as follows

$$Y = f(X_1, X_2, X_3), \tag{9}$$

where X_1, X_2, X_3 – linguistic variables, which describe thermo-physical, physic-mechanical and durability indicators as linguistic variables, influencing the reliability of ensuring the energy efficiency of heat-insulating construction products made of the straw.

The meaningful interpretation of the factors influencing the reliability of ensuring the energy efficiency of heat-insulating construction products made of straw and the corresponding set of linguistic evaluations is described by relations (10), (11), (12).

A linguistic variable describing the thermo-physical factors influencing the reliability of the energy efficiency of heat-insulating construction products made of straw can be represented by the ratio

$$X_1 = f(X_{11}, X_{12}, X_{13}, X_{14}, X_{15}) \tag{10}$$

where X_{11} – specific heat capacity of the insulating building product c is determined on the universal sets $U(X_{11})$ = (800; 1300; 1800) (J/(kg×K). Linguistic values of this factor are given by the term set

T(X_{11}) = <low, medium, high>;

X_{12} – thermal conductivity of heat-insulating construction product is determined on the universal set $U(X_{12})$ = (0.07; 0.10; 0.15; 0.20; 0.25), (W/m×K). The linguistic variable of this factor is given by the term set $T(X_{12})$ = <low, below average, average, above average, high>;

X_{13} – heat absorption coefficient of thermal insulation material of a construction product is determined on the universal set U(X_{13}) = (0.5; 1.0; 1.5) (W/m^{2}K). The linguistic variable of this factor is given by the term set T(X_{13}) = <low, medium, high>;

X_{14} – vapor permeability coefficient of thermal insulation material of the construction product is determined on the universal set $U(X_{14})$ = (0.02; 0.04; 0.06) (mg/m× h×Pa). The linguistic variable of this factor is given by the term set $T(X_{14})$ = <low, medium, high>;

X_{15} – the coefficient of air permeability of the thermal insulation material of the construction product is determined on the universal set $U(X_{15})$ = (0.15; 0.35; 0.45) (kg/m^{3}h). The linguistic variable of this factor is given by the term set $T(X_{15})$ = <low, medium, high>;

X_{16} – the dimensionless indicator of thermal inertia D, which is determined by [30] which characterizes the attenuation of temperature fluctuations inside the structure and for multilayered wall assembly (as usual) could be calculated as follows

$$\sum_{i=1}^{n} D_i = \sum (S_i \cdot R_i), \tag{11}$$

where $S_i = \sqrt{\dfrac{2\pi\lambda_i c_i \rho_i}{T}}$ – heat absorption coefficient of the i-th layer of the wall assembly (W/m^2×K);

T – the value of the oscillations period, s, which for practical calculations is usually taken equal to the 24-hour daily period;

λ_i – the thermal conductivity of the i-th layer material of the wall assembly, W/m×K;

c_i – specific heat capacity of the i-th layer material of the wall assembly (J/(kg×K);

ρ_i – density of the i-th layer material of the wall assembly, kg/m^3.

The dimensionless indicator of thermal inertia D of the heat-insulation material of the construction product is determined on the universal set

$U(X_{16})$ = (2; 6; 10). The linguistic variable of this factor is given by the term set $T(X_{16})$ = <low, medium, high>.

A linguistic variable describing the physic-mechanical factors influencing the reliability of the efficiency of the heat-insulating building materials from a straw can be represented by the ratio (12)

$$X_2 = f(X_{21}, X_{22}, X_{23}, X_{24}) \tag{12}$$

where X_{21} is the density of the heat-insulating construction product determined on the universal set $U(X_{21})$ = (25; 50; 75; 100; 125) (kg/m^3). Linguistic values of this factor are given by the term set $T(X_{21})$ = <low, below average, average, above average, high>;

X_{22} – compressive strength of the thermal insulation material of the construction product is determined on the universal set $U(X_{22})$ = (1, 2, 3, 4, 5) (arbitrary units). The linguistic variable of this factor is given by the term set $T(X_{22})$ = <low, below average, average, above average, high>;

X_{23} – frost resistance of thermal insulation material of a construction product is determined on the universal set $U(X_{23})$ = (1, 3, 5) (arbitrary units). The linguistic variable of this factor is given by the term set $T(X_{23})$ = <low, medium, high>;

X_{24} – sound absorption of thermal insulation material of a construction product is determined on the universal set $U(X_{24})$ = (20; 30; 40) (dB). The linguistic variable of this factor is given by the term set $T(X_{24})$ = <low, medium, high>.

The linguistic variable that describes the durability indicators as factors influencing the reliability of the energy efficiency of heat-insulating materials made of straw can be represented by the equation (13)

$$X_3 = f(X_{31}, X_{32}, X_{33}) \tag{13}$$

where X_{31} – fire resistance of heat-insulating material of a construction product is determined on the universal set $U(X_{31})$ = (15; 30; 45; 60; 90) (minutes). The linguistic variable of this factor is given by the term set $T(X_{31})$ = <low, below average, average, above average, high>;

X_{32} – chemical resistance of heat-insulating material of a construction product is determined on the universal set $U(X_{32})$ = (1, 3, 5) (arbitrary units). The linguistic variable of this factor is given by the term set $T(X_{32})$ = <low, medium, high>;

X_{33} – biological resistance of heat-insulating material of a construction product is determined on the universal set $U(X_{33})$ = (1, 3, 5) (arbitrary units). The linguistic variable of this factor is given by the term set $T(X_{33})$ = <low, medium, high>.

The knowledge matrix for the approximation of dependence (9) using fuzzy rules of type "IF-THEN" by taking into account the accepted gradations of terms is given in Table 1.

Table 1.
Fuzzy knowledge matrix for equation (9)

IF			THEN
X_1	X_2	X_3	Y
L	L	L	L
L	L	BA	
L	BA	L	
BA	L	L	
L	BA	BA	BA
BA	L	BA	
BA	BA	L	
BA	BA	BA	
A	A	A	A
BA	A	A	
A	BA	A	
A	A	BA	
AA	AA	AA	AA
AA	AA	A	
AA	A	AA	
A	AA	AA	
AA	H	H	H
H	H	H	
H	AA	H	
H	H	AA	

Linguistic expressions, given in the knowledge matrix for the approximation of the dependence (9) in Table1 corresponds to the system of the fuzzy logic equations, which characterize the membership surface of the linguistic variable, which is objective function – the reliability of ensuring the energy efficiency of heat-insulating construction products made of straw by the corresponding qualitative term (formulae 14–18):

$$\mu_L(Y) = \mu_L(X_1) \wedge \mu_L(X_2) \wedge \mu_L(X_3) \vee \mu_{BA}(X_1) \wedge \\ \wedge \mu_L(X_2) \wedge \mu_L(X_3) \vee \mu_L(X_1) \wedge \mu_{BA}(X_2) \wedge \\ \wedge \mu_L(X_3) \vee \mu_L(X_1) \wedge \mu_L(X_2) \wedge \mu_{BA}(X_3); \tag{14}$$

$$\mu_{BA}(Y) = \mu_L(X_1) \wedge \mu_{BA}(X_2) \wedge \mu_{BA}(X_3) \vee \mu_{BA}(X_1) \wedge \wedge \mu_{BA}(X_2) \wedge \mu_{BA}(X_3) \vee \mu_{BA}(X_1) \wedge \mu_{BA}(X_2) \wedge \wedge \mu_L(X_3) \vee \mu_{BA}(X_1) \wedge \mu_L(X_2) \wedge \mu_{BA}(X_3); \quad (15)$$

$$\mu_A(Y) = \mu_A(X_1) \wedge \mu_{BA}(X_2) \wedge \mu_A(X_3) \vee \mu_{BA}(X_1) \wedge \wedge \mu_A(X_2) \wedge \mu_A(X_3) \vee \mu_A(X_1) \wedge \mu_A(X_2) \wedge \wedge \mu_A(X_3); \quad (16)$$

$$\mu_{AA}(Y) = \mu_{AA}(X_1) \wedge \mu_{AA}(X_2) \wedge \mu_{AA}(X_3) \vee \vee \mu_{AA}(X_1) \wedge \mu_{AA}(X_2) \wedge \mu_A(X_3) \vee \mu_{AA}(X_1) \wedge \wedge \mu_A(X_2) \wedge \mu_{AA}(X_3) \vee \mu_A(X_1) \wedge \mu_{AA}(X_2) \wedge \wedge \mu_{AA}(X_3); \quad (17)$$

$$\mu_H(Y) = \mu_{AA}(X_1) \wedge \mu_H(X_2) \wedge \mu_H(X_3) \vee \mu_H(X_1) \wedge \wedge \mu_H(X_2) \wedge \mu_H(X_3) \vee \mu_H(X_1) \wedge \mu_H(X_2) \wedge \vee \mu_H(X_1) \wedge \mu_{AA}(X_2) \wedge \mu_{AA}(X_3); \quad (18)$$

According to the mathematical apparatus of fuzzy logic [27], the influence of quantitative and qualitative factors on the objective function is taken into account by the membership function.

The membership function is a set of values of μ (μ_i) for all $i = 1, \ldots, n$, which must be determined. The solution of the problem is based on the distribution of the belonging degrees of the universal set, which is represented by the linguistic variable Y, according to their ranks. Rank characterizes the significance of each influencing factor as linguistic variables (X_i). A matrix is compiled for each degree of belonging to the fuzzy evaluation term. A nine-point Saati scale [28] was used to expertly evaluate the elements of the matrix.

In this paper, the algorithm of the membership function's calculation is explained in the example of the influence factor X_{21} – density of heat-insulating material. As it was revealed above, this factor is characterized by the corresponding universal set $U(X_{21})$ = (25; 50; 75; 100; 125) (kg/m^3). It should be mentioned that the designing method of these membership functions is based on the pairwise comparison, as described in [31].

The linguistic evaluation used the term set $T(X_{21})$ = <low, less than average, medium, more than average, high>. The matrix $A_{low}(X_{21})$, which characterizes the pairwise comparisons of different values of the density of the heat-insulating material in terms of their proximity to the term "Low", is filled as below (19)

$$A_{low}(X_{21}) = \begin{array}{c|ccccc} & U_1 & U_2 & U_3 & U_4 & U_5 \\ U_1 & 1 & 6/8 & 4/8 & 2/8 & 1/8 \\ U_2 & 8/6 & 1 & 4/6 & 2/6 & 1/6 \\ U_3 & 8/4 & 6/4 & 1 & 2/4 & 1/4 \\ U_4 & 8/2 & 6/2 & 4/2 & 1 & 1/2 \\ U_5 & 8 & 6 & 4 & 2 & 1 \end{array} \quad (19)$$

According to the matrix (19), the calculation of the individual memberships U_1, U_2, U_3, U_4 and U_5 to the term "low" is performed as follows:

$$\mu_L(U_1) = \frac{1}{1+6/8+4/8+2/8+1/8} = 0.38,$$

$$\mu_L(U_2) = \frac{1}{8/6+1+4/6+2/6+1/6} = 0.29,$$

$$\mu_L(U_3) = \frac{1}{8/4+6/4+1+2/4+1/4} = 0.19,$$

$$\mu_L(U_4) = \frac{1}{8/2+6/2+4/2+1+1/2} = 0.10,$$

$$\mu_L(U_5) = \frac{1}{8+6+4+2+1} = 0.05.$$

According to the abovementioned method of finding the membership degree to the term "Low", matrices of pairwise comparisons for the terms "Below the Average", "Average", "Above the average" and "High" and the individual membership degrees are calculated respectively.

To facilitate the comparison of all membership degrees, their normalization by dividing to the maximum value is performed as shown below in formula (20)

$$\mu_L(U_i)_{norm} = \frac{\mu_L(U_i)}{\max(\mu_L(U_i))}, \; i = 1,\ldots,5. \quad (20)$$

Thus, the normalized values of the terms "Low", "Below the Average", "Average", "Above the Average" and "High" calculated by formulas (18), (19) for the linguistic variable "density" are given below. The numerator shows the normalized values of membership functions $\mu_{\text{"Density"}}(U_{\text{"Density"}})$, the denominator is a universal set U for the linguistic variable "Density":

$$\text{density "Low"} = \left\{\frac{1}{25};\frac{0,75}{50};\frac{0,5}{75};\frac{0,25}{100};\frac{0,13}{125}\right\};$$

$$\text{density "Below the average"} = \left\{\frac{0,78}{25};\frac{1}{50};\frac{0,56}{75};\frac{0,33}{100};\frac{0,11}{125}\right\};$$

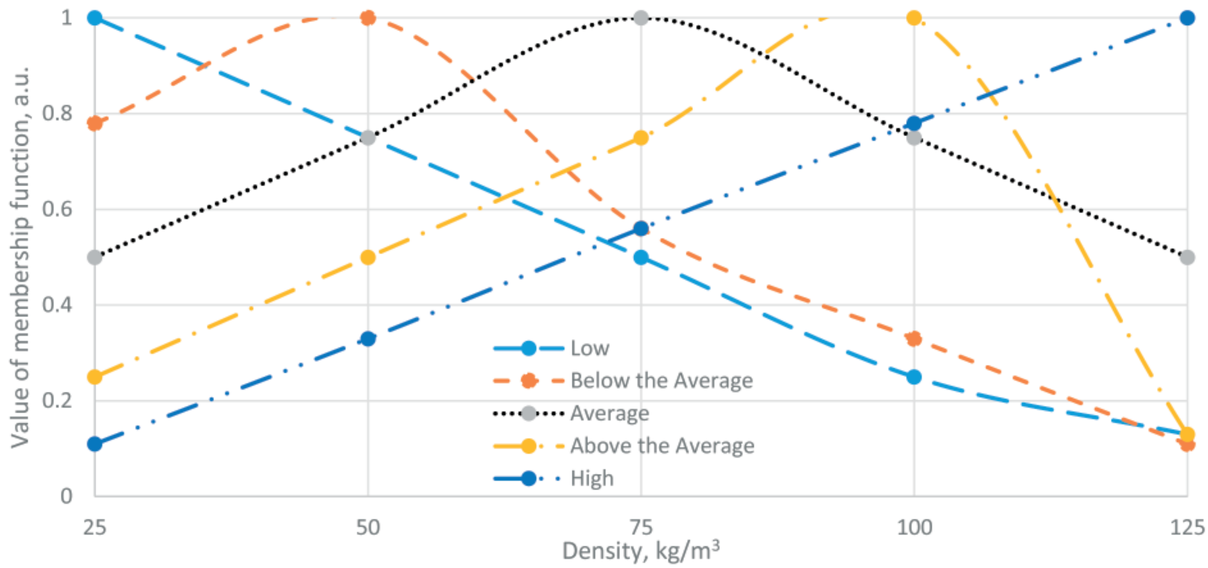

Figure 2.
Membership functions for the linguistic variable "Density"

density "Average" $= \left\{ \frac{0,5}{25}; \frac{0,75}{50}; \frac{1}{75}; \frac{0,75}{100}; \frac{0,5}{125} \right\}$;

density "Above the average"

$$\left\{ \frac{0,25}{25}; \frac{0,5}{50}; \frac{0,75}{75}; \frac{1}{100}; \frac{0,13}{125} \right\};$$

density "High" $\left\{ \frac{0,11}{25}; \frac{0,33}{50}; \frac{0,56}{75}; \frac{0,78}{100}; \frac{1}{125} \right\}$.

Graphic representation of membership functions for linguistic variable X_{21} ("Density") as the factors of influence on the objective function is shown in Fig. 2.

The obtained fuzzy sets (Fig. 2) indicate that the energy efficiency of heat-insulating materials made of straw for the influence factor X_{21} "Density" have the following values. The term "Low" is characterized by an inverse direct proportional dependence of the fuzzy set on the density of the material. The impact factor has the highest value at 25 kg/m^3, the minimum for 125 kg/m^3. The term "High" is characterized by a directly proportional relationship, with the lowest value for 25 kg/m^3, and the highest for 125 kg/m^3. For the factors of influence "Below the Average", "Average" and "Above the Average" the nature of the dependence is curvilinear. The highest value for $\mu(X_{21}) = 1$ for a density of 50 kg/m^3, for the term "Average" – 75 kg/m^3, and "Above the Average" – 100 kg/m^3.

The considered technique allows constructing graphic dependences for the other factors of influence resulting in the inference tree (see Fig. 1). Graphical interpretation of the obtained dependences will allow estimating the influence of each factor – thermo-physical, physic-mechanical and durability parameters.

6. DISCUSSION OF THE RESULTS OF THE RESEARCH

From Fig. 2, it can be considered, that obtained membership functions for the linguistic variables "Density", are only the first step in an approximation of an objective function. Further researches should be conducted and they could be dedicated to fine-tuning this previous model data, with that, obtained from the results of the real field research and further analysis.

It is obvious, that proposed hierarchical model of the inference tree (see Fig. 1) for the objective function could be widened and supplemented by other, significant influence factors. Due to the lack of real, field data, the determination of the reliability ensuring the energy efficiency of heat-insulating materials made of straw is still an ambiguous challenge.

In the authors' opinion, the more real data could be collected, the more objective and comprehensive will be an assessment of the energy efficiency reliability ensuring in the terms of abovementioned influence factors.

7. CONCLUSIONS

1. With the aid of apparatus of the fuzzy logic and linguistic variables, a hierarchical model in the form of a logical inference tree is proposed, which contains the main quantitative and qualitative factors influencing the objective function – reliability of energy efficiency of heat-insulating building materials made of straw.
2. The calculation of the parameters of the mathematical model for evaluating the reliability of ensuring the energy efficiency of heat-insulating building materials made of straw on the example of the linguistic variable "Density" is conducted. Numerical values of its fuzzy set with a graphic interpretation of results are calculated. Further researches in this field should be conducted and could be dedicated to a real assessment of the reliability and fine-tuning of this previous model data, with that, obtained from the results of the real field research.
3. According to the authors' opinion, the proposed fuzzy-probabilistic approach can be used as an additional tool in Building Energy Modeling (BEM) as well in the decision-making process to estimate the construction and operation cost of buildings.
4. This will allow evaluating, and, if necessary, increasing the reliability of energy efficiency of multilayered thermal insulation envelope structures of any type of materials, including straw.

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