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MANAGEMENT MODEL FOR THE CONSTRUCTION'S WASTE USE IN WALLS MANUFACTURING

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Abstract
The mathematical model, which could be represented as a fuzzy inference tree for project man-agement aimed at waste usage in wall manufacturing, is proposed in the article. The factors classification that affect production's environmental and economic efficiency is presented. The proposed ecological and economic efficiency criterion and influence factors are linguistic variables consisting of fuzzy terms on the corresponding universal sets. The proposed hierarchical system of mathematical models allows the intelligent choice of proper building material, depending on the influence of environmental parameters, socio-economic parameters, and engineering and technological parameters of a building object, based on fuzzy logical expressions "IF-THEN". The proposed model could be used as a support system model in the decision-making process at the early feasibility stage. Estimating pros and cons based on the results of a virtual experiment in terms of proposed criterion value for specific construction waste allows proper planning of construction waste usage in the construction sector. The proposed model can be used as a design and engineering tool in the decision-making process for forecasting the ecological and economic efficiency of the use of waste in the manufacture of walls.

Keywords: **Modelling; Construction waste; Concrete waste recycling; Envelope materials; Linguistic variable; Fuzzy logic.**

1. INTRODUCTION

Nowadays, according to the economic and social development and the urbanisation pace acceleration, new projects and the reconstruction of old buildings have produced substantial construction waste. In China, construction waste accounts for 30–40% of the overall urban waste volume. According to the 500–600 waste tons per 10,000 square meters standard, China is estimated to add approximately 30 billion square meters of building space by 2025, resulting in an astonishing amount of newly generated construction waste. [1–3]. Suppose the traditional disposal method of landfill or open stacking is continued. In that case, it will cause more significant damage to the ecosystem.

With the increasing prominence of this problem and the emergence of the circular economy concept, people gradually attach importance to the resource value of construction waste.

Many other countries require official proof that the waste is not recyclable when receiving waste at landfills. In Finnish legislation, the owner's responsibility for disposal is enshrined [4].

Using construction waste recycling technology to produce structural and heat-insulating wall materials will reduce the costs of expensive binders in raw material mixtures. Scientific developments provide for the application in the construction practice of the resource-saving technology of forming wall materials using autoclaveless technology, which in turn allows transformation of the obtained results in the conditions of the construction site without the use of special equipment and complex technologies [5, 6]. The main question arises for practitioners: how to reduce the amount of construction waste and use it rationally [7–14]. Construction industry needs to bring systematic, structural and behavioral innovation to reduce the consumption of primary resources and waste generation [15]. Waste generation is highly dependent on various contextual factors such as lack of management, improper worker skill, error in contract documents and poor quality control [16]. So, the large quantities of waste reduce the utility of construction operations and impact the financial viability through cost overrun and excess contingency utilization [17]. Various methods are used to assess current waste disposal practices, quantitative and qualitative impact factors, for example Saunders's research onion model [18, 19]. The objectives of the paper was to classify the factors of influence on waste and to develop a methodology for evaluating the most rational option for the use of waste using the indicator of ecological and economic efficiency.

2. PURPOSE AND TASKS OF THE RESEARCH

The task is to develop new and research existing models of construction waste management. The model will make it possible to establish the optimal production volume of construction products under existing environmental restrictions and explore practical ways of developing ecological systems during the entire investment process of using construction waste.

The authors intend to consider the following problems:

1. Creating a hierarchical classification system for quantitative and qualitative factors impacting waste management based on expert's fuzzy knowledge base.
2. Creating a mathematical model to comprehensively evaluate the environmental and economic effectiveness of producing external envelopes from construction waste.
3. The utilisation of linguistic variables through fuzzy rules and fuzzy logical operations in this particular model.
4. To create a waste management model, improve the economic mechanism of natural environment protection at all product life cycle stages, and reduce the technological load and the complexity of extracting valuable components.

3. METHODS OF RESEARCH

3.1 Current state of the art of structure of mathematical model

The mathematical model of the application of materials for walls from construction waste must correspond to the actual state of the art and reflect the causal relationships of the investigated object. Three main steps can perform the modelling process:

1) analysis of theoretical regularities characteristic of the object under study and empirical data on its structure and features;
2) determination of methods that can be employed to address the problem;
3) considering the analysis of the results. A situation often arises in mathematical modelling when the studied ecological and economic system has an overly complex structure.

Even though there has been similar research over recent years [20], the comprehensive models involving the whole range of ecological, economic and sustainable parameters is still an ambiguous challenge, which would fully cover all the main features and connections of such a system. Thus, there is a need to simplify the researched object and exclude and analyse some of its secondary features. It is necessary to bring this simplified system under the class of already-known structures subject to mathematical description and analysis. At the same time, the degree of simplification must consider all the features of the ecological and economic object and correspond to the purpose of the study. An emphasis point of the first modelling step is to clarify the determination of the goal function of the model designing of building the model, the criterion definition for the comparison of different solutions [21, 22].

From the economic analysis view, such parameters could be as follows: the highest profit, the lowest production costs, the maximum percentage of equipment engagement, labour productivity, etc. The objective function reflects such a criterion in mathematical programming problems. At the same time, it is assumed that the resources that must be allocated to produce products are limited. Therefore, it is vital to determine which resources are crucial for the research process, their supply, and the costs of each type of resource per production unit. All constraints reflecting the economic process must be consistent; at least one solution to the problem must consider all constraints. After combining the objective function equation and the constraints system, we get a mathematical model of the economic process. The second modelling stage selects the most rational mathematical method for solving the problem. Many methods are known for solving linear programming problems: simplex, potentials, and others [23].

This model should allow for obtaining the most rational solution and accurate economic estimates. Excessive detail complicates the construction of the model, often does not give any advantages in analysing economic relationships and does not enrich the conclusions. Excessive model consolidation leads to the loss of essential ecological and economic information and an inadequate representation of actual conditions. The third modelling stage is a comprehensive analysis of the result obtained while studying an economic phenomenon or process. The criterion of reliability and quality of the model is practice, correspondence of the obtained results and conclusions to actual conditions of production, and economic meaningfulness of the obtained estimates. Suppose the obtained results do not correspond to actual production conditions. In that case, the reasons for the discrepancy are the lack of reliability of the information and the inconsistency of the applied mathematical methods and schemes with the characteristics of the economic object under study. According to the authors [23], the following steps are necessary to solve such problem:

1. Take into account the environmental factors in economic and mathematical models. Models of this class preserve the traditional structure of economic-mathematical models and contain additional variables and connections characterising the ecological subsystem. In such models, there are natural raw materials and materials pollutants flows. The latest processes that determine the ecosystem dynamics are not described in the model or are described with much less detail than production and economic activity.
2. Taking into account anthropogenic action in ecosystem models. When building models of this class, models of mathematical ecology are taken as a basis, and anthropogenic activity is considered an exogenous influence on the ecosystem. Their feature is the presence of an economic criterion, according to which the policy of exploitation of the population or community is carried out.

The experience accumulated during the generalisation of mathematical economics and mathematical ecology models made it possible to construct complex ecological and economic models, including two main blocks describing economic and ecological processes [16]. At the same time, each block necessarily contains equations that connect the variables of the ecological and economic subsystems [22].

3.2. Present models

Classical representatives of the models are the inter-industry balance model of Leontiev-Ford [23]and the kinetic model of Mono-Ierusalymskyi [22], respectively. The Leontiev-Ford model describes two groups of industries: industries of material production and industries for the destruction of harmful waste:

$$x_1 = A_{11} \times 1 + A_{12} \times 2 + y_1; \tag{1}$$

$$x_2 = A_{21} \times 1 + A_{22} \times 2 + y_2; \tag{2}$$

Equation (1) reflects the balance of the distribution of manufactured products x_1: for consumption by the primary production $A_{11}\times 1$, auxiliary production – $A_{12}\times 2$, and the final product y_1, which is determined by the demand for products. The pollutant balance (2) reflects the volume of pollutants from all production activities $A_{21}\times 1 + A_{22}\times 2$ and the permissible sizes of non-destructive pollutants y_2, which are determined by the accepted sanitary and hygienic standards. Let us add that the economic content of the model requires that all its variables be integral.

The Leontiev-Ford model is effectively used to create market mechanisms of ecological and economic interaction. The main directions of such use should be noted:

1. The model should be considered in incremental quantities. Assume that the final product is stable.

We obtain analytical expressions for the economy of total output and the economy of pollutant destruction, which make it possible to estimate the economy of the primary and auxiliary industries when the emission of pollutants into the environment increases by a given amount. We get an answer to production costs when reducing environmental pollution by a given value.

2. The model can be used for product pricing, considering the necessary environmental costs of producing these products.
3. The model can be used to determine the environmental tax.
4. The model makes it possible to investigate the optimal regional structure of production in connection with the possibility of interregional exchange of products and to ensure ecological environmental requirements.

In the management of the construction investment process, attention should be paid to two concepts: the aspect of management and the aspect of environmental protection. This aspect is considered by the developed scheme of the model of integrated ecological and economic management of the production of external walls from construction waste (see Fig. 1). The concept of "integrated" management means, firstly, the harmonious interaction of the general production management structure and the ecological and economic management structure being implemented; secondly, subordinating the entire production investment process to the goal of reducing the burden on nature. Traditional methods for the multifactorial analysis of complex systems do not allow describing the cause-and-effect relationships between the impact parameters and the predicted value with the help of factors that consider the influence of their qualitative parameters on decision-making.

The Leontiev-Ford model is useful for understanding the interrelationships in production processes, forecasting the impact of changes in the production of one industry on others, and the impact of construction on the environment. It is an important tool in economic science for the analysis of inter-industry relations and interaction in production. This model became the basis for selecting the final indicator in the paper – the indicator of ecological and economic efficiency.

3.3. Fuzzy set approach

Using the theory of fuzzy sets allows the technical and economic substantiation of the development of an investment project for constructing an object to make optimal organisational and technological decisions to obtain ecological, economic and social effects in construction based on the results of a virtual experiment. This method is based on expert modelling forecasting using quantitative and qualitative influencing factors [25]. Considering the main influence factors, the mathematical model of a comprehensive assessment of the ecological and economic efficiency of the production of external walls from construction waste has been developed. Linguistic variables applied in this model are based on fuzzy rules and logical operations. We will consider the technique of forecasting ecological and economic efficiency based on the apparatus of fuzzy logic in stages.

Under this mathematical framework, the fuzzy set representing the term F is defined as parameters set:

$$F = \frac{\mu_F(u_1)}{u_1} + \frac{\mu_F(u_2)}{u_2} + \ldots + \frac{\mu_F(u_n)}{u_n}, \tag{3}$$

where (u_1, u_2,…, u_n) represents the universal set U upon which a fuzzy set is defined $F \in U$; $\mu_F(u_i)$ represents the membership degree of the element $u_i \in U$ in the fuzzy set F.

The logical inference is described using a system of fuzzy logical statements, respectively:

We choose the minimum value under this condition:

$$\mu_C(u) = \mu_A(u) \wedge \mu_B(u). \tag{4}$$

We choose the maximum value under this condition:

$$\mu_D(u) = \mu_A(u) \vee \mu_B(u). \tag{5}$$

Fuzzy logical *AND* (∧) *OR* (∨) are executed following the established rules:

$$\mu_{A \wedge B}(u) = \min(\mu_A(u), \mu_B(u)). \tag{6}$$

$$\mu_{A \vee B}(u) = \max(\mu_A(u), \mu_B(u)). \tag{7}$$

The distribution rule for membership degrees, as per the normalisation condition ($\mu_1 + \mu_2 + \ldots \mu_n$) = 1, is expressed as follows in the form of a relation:

$$\frac{\mu_1}{r_1} = \frac{\mu_2}{r_2} = \ldots = \frac{\mu_n}{r_n}, \tag{8}$$

where $r_i = r_F(u_i) = u_i$ – represents the rank or numerical value that signifies the element's importance in the characteristic creation and is described by the fuzzy term F.

$$\mu_i = \mu_F(u_i).$$

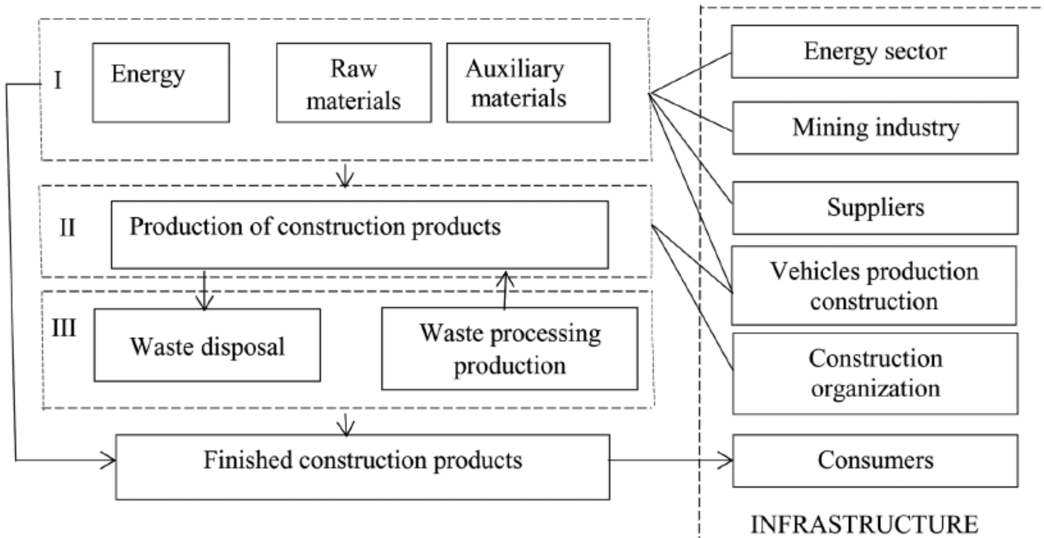

Figure 1.
Management model for the use of construction waste in wall manufacture

4. CALCULATION OF THE PROPOSED MODEL PARAMETERS

The management model of the construction production of wall materials from construction waste is connected with many industries involved in creating construction products. The model connects three main stages of the life cycles of the creation of construction products (Fig. 1). The first stage is extracting natural resources. This stage is determined by the amount of rationally consumed resources: water, energy, land and other resources. During construction, it is necessary to increase the efficiency of the use of resources and try to work without waste or reuse waste. Usually, many materials, energy, and water resources are used in construction. It is encouraging that the construction industry can achieve a net benefit of almost 2.5% of the total budgeted cost by reusing and recycling wasteful materials [26]. The authors of the article distinguish the main categories in waste management: waste management at the project level; waste management at the sectoral level and waste management at the national level. The second stage of the life cycle is the creation of construction products. At this stage, the amount of emissions into the environment is determined, the environmental impact is synthesised, the possibility of improving the environmental characteristics is assessed, and the optimal choice of the ecological and economic variant of construction products.

The third stage is the disposal and processing of waste. Using building materials from recycled raw materials reduces the depletion of natural resources and saves the customer and developer money. Reusable materials must be identified to determine the cost-effectiveness of construction waste recycling. Local separation and strict control of reusable materials are essential in all cases. Calculations carried out by authors [10] for the mining industry showed that the current production level could be ensured by reducing the volume of rock mass extraction by 20–25% due to producing 80% of construction materials from waste. At the same time, the cost of production will decrease by 10–15%, and the environmental conditions in mining areas will improve. It is necessary to apply recycling and reuse of materials. Building materials saved from destruction can be used many times. An effective program to control the waste generated during construction can help ensure its reuse. The structure of the study is presented in Figure 2.

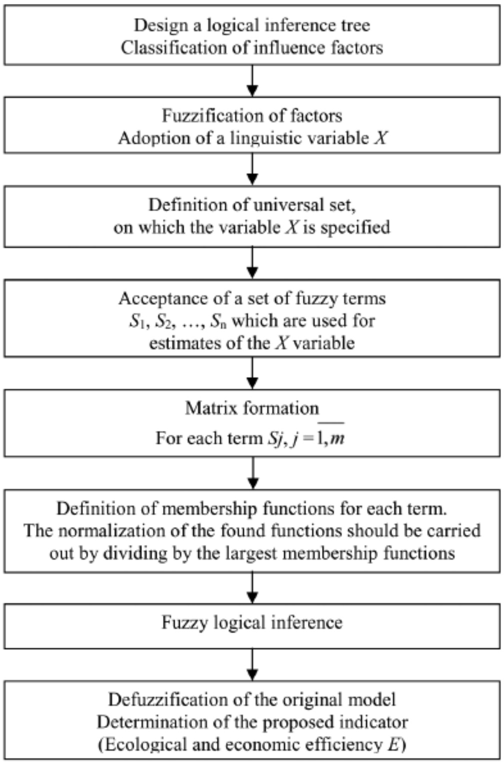

Figure 2.
The structure of the study

Stage 1. Design a logical inference tree. The tree of logical inference reflects the classification of factors affecting the proposed criterion – ecological and economic efficiency E (see Fig. 3).

This methodology uses fuzzy logic that can be used in many fields, including engineering, economics, and management. It allows you to model reality taking into account vagueness and uncertainty. Some influencing factors in our model are fuzzy, and fuzzy logic allows mathematical description of this fuzziness. Fuzzy logic also has its limitations and requires proper definition and setting of parameters for effective application.

The linguistic variable E can be represented in the form of a ratio:

$$E = f_E(X, Y, Z), \tag{9}$$

where X is a linguistic variable (LV) describing environmental parameters;

Y – LV describing socio-economic parameters; Z – LV describing engineering and technological solutions.

LV, which describes environmental parameters, can be represented by a ratio

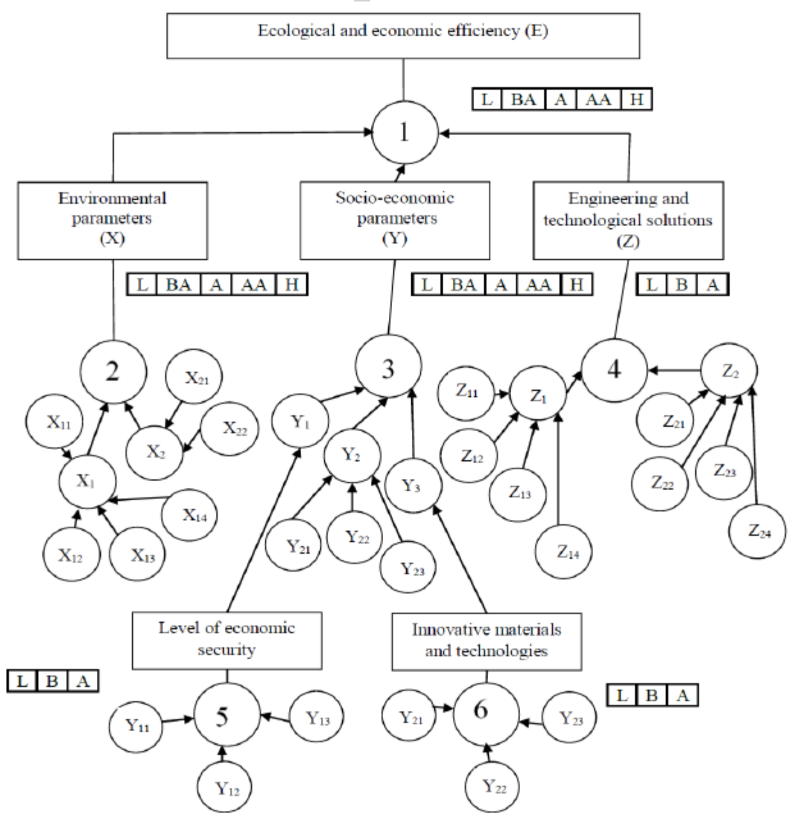

Figure 3.
The hierarchy of relationships is represented as a logical inference tree of factors affecting the management of the construction waste external envelopes' production

$$X = f_X(X_1, X_2), \quad (10)$$

where X_1 – LV that describes environmental problems; X_2 – LV, which describes the level of environmental awareness;

LV, which describes socio-economic parameters, can be represented by a ratio

$$Y = f_Y(Y_1, Y_2, Y_3, Y_4), \quad (11)$$

where Y_1 is the LV that describes the level of economic security;

Y_2 – LV, which characterises state regulation; Y_3 – LV, which characterises innovative materials and technologies offered by the market.

LV, which describes engineering and technological solutions, can be represented by a ratio

$$Z = f_Z(Z_1, Z_2), \quad (12)$$

where Z_1 is the LV that describes the durability of the walls;

Z_2 – LV, which describes the construction characteristics of the walls;

A linguistic variable describing environmental problems can be shown as follows

$$X_1 = f_{X1}(X_{11}, X_{12}, X_{13}, X_{14}), \quad (13)$$

where X_{11} – LV "environmental pollution"; X_{12} – LV "exhaustion of natural resources"; X_{13} – LV "content of radionuclides"; X_{14} – LV "temperature in the room".

The linguistic variable describing the level of environmental awareness can be calculated as follows

$$X_2 = f_{X2}(X_{21}, X_{22}), \quad (14)$$

where X_{21} is the LV "responsibility"; X_{22} is the LV "environmental education". The linguistic variable Y_1 describing the level of economic security can be written as follows

$$Y_1 = f_{Y1}(Y_{11}, Y_{12}, Y_{13}), \quad (15)$$

where Y_{11} is the LV "specific parameter of economic costs caused by a unit of the i-th type of pollution"; Y_{12} – LV "specific parameter of economic costs determined by a single parameter of the i-th eco-destructive effect on the human body";

Y_{13} – LV "specific parameter of economic costs caused by a single parameter of the nth eco-destructive action on natural resources".

A linguistic variable characterising state regulation can be obtained from the equation

$$Y_2 = f_{Y2}(Y_{21}, Y_{22}, Y_{23}), \quad (16)$$

where Y_{21} is the LV "environmental taxes"; Y_{22} – LV "criminal liability"; Y_{23} – LV "environmental fines".

The linguistic variable Y_3, which characterises innovative materials and technologies, can be obtained from the equation

$$Y_3 = f_{Y3}(Y_{31}, Y_{32}, Y_{33}), \quad (17)$$

where Y_{31} are LV "environmental materials"; Y_{32} – LV "innovative technologies", Y_{33} – LV "industriality".

A linguistic variable describing the durability of walls can be calculated according to the expression

$$Z_1 = f_{Z1}(Z_{11}, Z_{12}, Z_{13}, Z_{14}), \quad (18)$$

where Z_{11} is LV "frost resistance"; Z_{12} – "moisture resistance"; Z_{13} – LV "bio resistance", Z_{14} – LV "fire resistance".

A linguistic variable describing the construction characteristics of walls can be written as proposed in the following expression

$$Z_2 = f_{Z2}(Z_{21}, Z_{22}, Z_{23}, Z_{24}), \quad (19)$$

where Z_{21} is LV "porosity"; Z_{22} – LV "sound insulation"; Z_{23} – LV "thermal insulation"; Z_{24} – LV "mass".

Stage 2. Fuzzification of factors. Selection of fuzzy terms for linguistic evaluation of factors and formalisation of these terms using membership functions.

Factor Z_{21} – "porosity"

$$\bigcup(Z_{21}) = [0...100]\%.$$

For the linguistic assessment of the factor Z_{21}, the term set is used:

$$T(Z_{21}) = < low,\ below\ average,\ average,$$
$$above\ average,\ high > .$$

One of the possible methods to obtain the values of belonging degree of membership functions is AHP [27]. A model consisting of three hierarchical levels has been constructed to establish the integral criterion – ecological and economic efficiency E. This model illustrates how the thermophysical and physical-mechanical attributes of organic natural materials impact the target function (criterion of ecological and economic efficiency E), which can be defined as a quantitative, comprehensive representation of a parameter considering the varied nature of its influencing factors (see Figure 3).

The following outlines the approach for developing a hierarchical model to assess various envelope materials' ecological and economic efficiency criterion E.

Using pairwise comparisons (as described in [27]), the importance of each criterion will be assessed and weighted for each alternative wall type. The weight assigned to each criterion signifies its contribution to the overall goal of ecological and economic efficiency.

Each of these local priorities is represented as a matrix (as discussed in [25, 27]), which is populated in the following manner.

The resulting vector, indicating the advantages of a specific matrix in pairwise comparisons, is considered acceptable if CR falls within the range of 0.10 to 0.20 [27].

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

$$A = \begin{bmatrix} 1 & \frac{r_1}{r_2} & \frac{r_1}{r_3} \dots \frac{r_1}{r_n} \\ \frac{r_2}{r_1} & 1 & \frac{r_2}{r_3} \dots \frac{r_2}{r_n} \\ \dots\dots & \dots & \dots\dots \\ \frac{r_n}{r_1} & \frac{r_n}{r_2} & \frac{r_n}{r_3} \dots 1 \end{bmatrix}, \quad (20)$$

r_1, r_2, r_3, n – represent the respective priority values for the assessed parameters within the matrix, which define the values of the studied parameters.

Once the row elements of the matrix (9) are known, the elements of all other rows are computed. The arbitrary element a_{jj}, where j is any value from 1 to n, is determined as $a_{jj} = r_i/r_j$ with known elements $a_{kj} = r_k/r_j$, k, and $i = \overline{1,n}$, where k and i range from 1 to n.

The advantage vector for each parameter represented by m_i is determined by computing the average geometric value of the elements in each row of the matrix and then dividing this value by the sum of all the average geometric values for the assessed parameters. This calculation is performed using the formula described in [27].

$$\sqrt[n]{1 \times \frac{r_1}{r_2} \times \frac{r_1}{r_3} \times \dots \times \frac{r_1}{r_n}} = m_1 \quad (21)$$

Subsequently, the advantage vector for the initial row of the matrix, as derived from formula (9), is computed, considering the average geometric values for each of the rows in the calculation, as per the following formula:

$$\frac{m_1}{m_1 + m_2 + \dots + m_n} = x_1 \quad (22)$$

where $x_1, x_2,, \dots x_n$ represent the advantage vectors for the first, second, up to the n-th row of the matrix, respectively. Following a similar procedure, the components of the eigenvector and advantage vector for the remaining mn rows are determined.

We utilise the components of our eigenvector associated with the largest eigenvalue $\eta_{\max}$ as the set of relative weights for the alternatives [27]. It is essential to ensure that $\eta_{\max} \geq n$ to assess the matrix's coherence.

To gauge the consistency within the matrix elements A, we employ the consistency index, denoted as CI

$$CI = \frac{(\eta_{\max} - n)}{n} - 1, \quad (23)$$

where n represents the rank of the matrix.

To evaluate the appropriateness of the consistency level, we employ the consistency ratio denoted as CR, which is calculated as follows:

$$CR = \frac{CI}{MRCI}, \quad (24)$$

where $MRCI$ stands for the random consistency index, which represents the average value calculated from many pairwise comparison matrices generated using a fundamental scale, as described in reference [27].

Tables 1 and 2 provide information about all the elements of the matrix, including its eigenvector $\eta_{\max}$, the pairwise comparison consistency index CI, and the consistency ratio CR, which pertain to the membership of terms «below average», «average», «above average» and «high» of fuzzy sets to Z_{21}. The matrix displays pairwise comparisons of various porosity values from the point of view of their belonging to the term "low" has the form (Table 1). In this paper, the method of constructing the belonging functions is considered in detail only with the example of the porosity effect of the material. Only the final results of membership functions are given for the rest of the factors.

Table 1.
The pairwise comparison matrix for the linguistic variable "porosity" low (Z_{21})

Comparison of the universal set of Z_{21} parameter	u_1	u_2	u_3	u_4	u_5
u_1	1	2/3	5/9	4/9	1/9
u_2	3/2	1	2/7	2/7	1/7
u_3	9/5	7/2	1	8/9	1/3
u_4	9/4	7/2	9/8	1	1
u_5	9	7	3	1	1

In this matrix (as shown in Table 1), each cell contains expert assessments of the relative importance of one influencing factor over another, using the widely used 9-point Saati scale [27]. The matrix is filled according to the following principle: a value greater than one is placed in a cell if the factor on the left is more important than the one above it concerning the specific criterion. Conversely, values less than one are entered in the corresponding cells when the factor on the left is less important than the factor above it concerning the same criterion.

Table 2.
Eigenvector η_{max}, consistency index *CI*, consistency ratio *CR* for "porosity" low Z_{21} matrix

Characteristic number of the vector, η_{max}	5.031
Consistency index, *CI*	0.126
Consistency ratio, *CR*	0.112

As shown in Table 2, the *CR* value of the linguistic variable "porosity" low (Z_{21}) matrix does not exceed the threshold value of consistency ratio, which is equal for 5×5 matrix dimensions – 0.12 [27]. Thus, it should be considered a consistent matrix.

For the matrix Low(Z_{21}), we obtain the degrees of belonging of the individual memberships $u_1 \dots u_5$ to the term "low":

$$\mu_{low}(u_1) = \frac{1}{1+\frac{2}{3}+\frac{5}{9}+\frac{4}{9}+\frac{1}{9}} = 0.36;$$

$$\mu_{low}(u_2) = \frac{1}{\frac{3}{2}+1+\frac{2}{7}+\frac{2}{7}+\frac{1}{7}} = 0.31;$$

$$\mu_{low}(u_3) = \frac{1}{\frac{9}{5}+\frac{7}{2}+1+\frac{8}{9}+\frac{1}{3}} = 0.13;$$

$$\mu_{low}(u_4) = \frac{1}{\frac{9}{4}+\frac{7}{2}+\frac{9}{8}+1+1} = 0.11;$$

$$\mu_{low}(u_5) = \frac{1}{9+7+3+1+1} = 0.04.$$

Likewise, we establish pairwise comparison matrices for the terms "below average", "average", "above average", and "high", along with their corresponding belonging degrees.

The next step will be the normalisation of the obtained results. Thus, the normalised value for $\mu_{low}(u_1) \dots \mu_{low}(u_5)$ parameter Z_{21} will be as follows.

$$\mu_{low}(u_1)_{normalized} = \frac{\mu_{low}(u_1)}{\max(\mu_{low}(u_1)\dots\mu_{low}(u_5))} = \frac{0.36}{0.36} = 1;$$

$$\mu_{low}(u_2)_{normalized} = \frac{\mu_{low}(u_2)}{\max(\mu_{low}(u_1)\dots\mu_{low}(u_5))} = \frac{0.31}{0.36} = 0.86;$$

$$\mu_{low}(u_3)_{normalized} = \frac{\mu_{low}(u_3)}{\max(\mu_{low}(u_1)\dots\mu_{low}(u_5))} = \frac{0.13}{0.36} = 0.37;$$

$$\mu_{low}(u_4)_{normalized} = \frac{\mu_{low}(u_4)}{\max(\mu_{low}(u_1)\dots\mu_{low}(u_5))} = \frac{0.11}{0.36} = 0.31;$$

$$\mu_{low}(u_5)_{normalized} = \frac{\mu_{low}(u_5)}{\max(\mu_{low}(u_1)\dots\mu_{low}(u_5))} = \frac{0.04}{0.36} = 0.13.$$

The final plot of fuzzy sets membership functions of parameter Z_{21} is shown in Fig. 4.

Stage 3. Construction of fuzzy knowledge matrices. The fuzzy knowledge matrix includes the results of a virtual experiment. The expert answers the question: "What will the linguistic assessment of the initial parameter be when combining the linguistic assessments of the factors?"

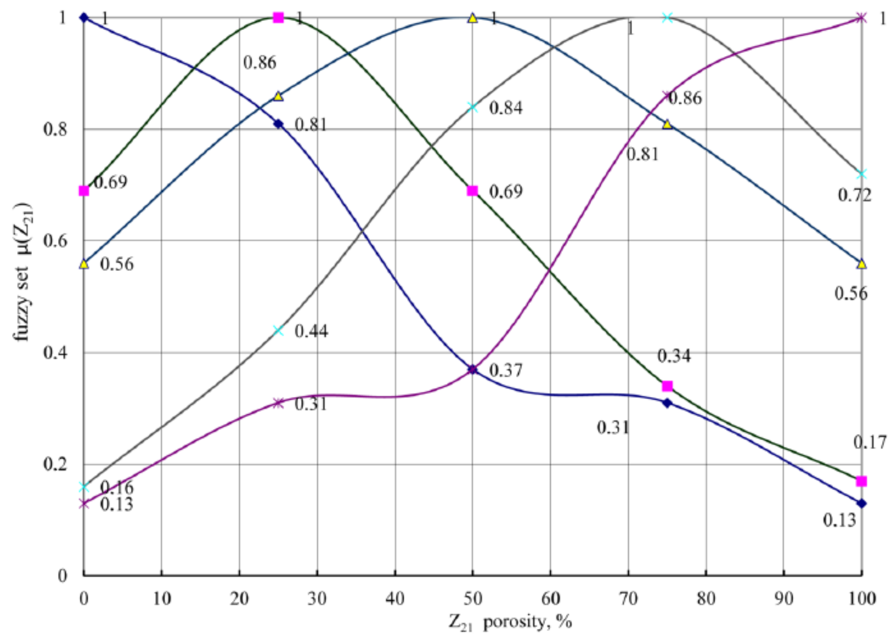

Figure 4.
Membership functions for the linguistic variable "porosity"

Table 3.
Fuzzy knowledge matrix related to equation (9)

IF			THEN
Environmental parameters (X)	Socio-economic parameters (Y)	Engineering and technological solutions (Z)	ecological and economic efficiency (E)
Low (L)	Low ( )	Low ( )	Low (L)
Below average (BA)	Low (L)	Low (L)	
Low (L)	Below Average (BA)	Low (L)	
Below Average (BA)	Below Average (BA)	Average (A)	Below Average (BA)
Average (A)	Below Average (BA)	Low (L)	
Below Average (BA)	Average (A)	Average (A)	
Below Average (BA)	Average (A)	Average (A)	Average (A)
Average (A)	Average (A)	Average (A)	
Average (A)	Low (L)	High (H)	
Above average (AA)	Above Average (AA)	Average (A)	Above Average (AA)
Average (A)	Above Average (AA)	High (H)	
Low (L)	High (H)	High (H)	
High (H)	High (H)	High (H)	High (H)
High (H)	Above Average (AA)	High (H)	
High (H)	High (H)	Average (A)	

The fuzzy matrix of knowledge considering the introduced qualitative terms for modelling the equation (17) is presented in the Table. 3.

Stage 4. Fuzzy logical inference. The technique of fuzzy logic inference, which is applied to the information collected in the previous stages, allows calculating the goal function criterion of ecological and economic efficiency that is predicted in the form of a fuzzy set using a system of "IF-THEN" statements that connect the fuzzy terms of the input and output changes using the operation AND and OR [25], which are accepted in the theory of fuzzy sets and correspond to the min and max operations. Linguistic expressions correspond to a system of fuzzy logical equations that characterise the surface of belonging of the variables to the corresponding term.

Linguistic statements given in Table 1 correspond to a system of fuzzy logical equations that characterise the surface of belonging of variables by the corresponding term:

$$\mu_L(E) = \mu_L(X) \wedge \mu_L(Y) \wedge \mu_L(Z) \vee \mu_{BA}(X) \wedge \mu_L(Y) \wedge$$
$$\wedge \mu_L(Y) \wedge \mu_L(Z) \vee \mu_L(X) \wedge \mu_{BA}(Y) \wedge \mu_L(Z);$$
$$\mu_{BA}(E) = \mu_{BA}(X) \wedge \mu_{BA}(Y) \wedge \mu_A(Z) \vee \mu_A(X) \wedge \mu_{BA}(Y) \wedge$$
$$\wedge \mu_L(Z) \vee \mu_{BA}(X) \wedge \mu_A(Y) \wedge \mu_L(Z);$$
$$\mu_A(E) = \mu_{BA}(X) \wedge \mu_A(Y) \wedge \mu_A(Z) \vee \mu_A(X) \wedge \mu_A(Y) \wedge$$
$$\wedge \mu_A(Z) \vee \mu_A(X) \wedge \mu_L(Y) \wedge \mu_H(Z);$$
$$\mu_{AA}(E) = \mu_{AA}(X) \wedge \mu_{AA}(Y) \wedge \mu_A(Z) \vee \mu_A(X) \wedge \mu_{AA}(Y) \wedge$$
$$\wedge \mu_{AA}(Y) \wedge \mu_H(Z) \vee \mu_L(X) \wedge \mu_H(Y) \wedge \mu_H(Z);$$
$$\mu_H(E) = \mu_H(X) \wedge \mu_H(Y) \wedge \mu_H(Z) \vee \mu_H(X) \wedge \mu_{AA}(Y) \wedge$$
$$\wedge \mu_H(Z) \vee \mu_H(X) \wedge \mu_H(Y) \wedge \mu_A(Z). \quad (25)$$

Stage 5. Defuzzification of the original model. It is necessary to perform a defuzzification procedure to move from the obtained fuzzy set to a quantitative estimate. This means converting fuzzy data into a clear form.

Defuzzification of fuzzy sets according to the "centre of gravity" technique results in a quantitative estimate of E at given values of influencing [25]

$$C_E^{*} = (X, Y, Z) = \frac{\sum_{i=1}^{l} C_E^{d_i} \times \mu_{d_i}(C_E)}{\sum_{i=1}^{l} \mu_{d_i}(C_E)}, \quad (26)$$

where l is the number of fuzzy terms for estimating the C_E variable;

d_i is the name of the i-th term, $i = \overline{1,l}$;

$\mu_{d_i}(C_E)$ is the degree of belonging C_E to the term d_i.

Substitute a number $C_E^{d_i}$ for the i-th term

$$C_E^{d_i} = \left[\underline{C_E} + \frac{\overline{C_E} + \underline{C_E}}{l-1} \times (i-1) \right], \quad (27)$$

Where $\underline{C_E}$ ($\overline{C_E}$) – is the smallest (largest) value of the variable C_E, and equation (27) will be as follows

$$C_E = \frac{\sum_{i=1}^{l} \mu_{d_i}(C_E) \left[\underline{C_E} + \frac{\overline{C_E} + \underline{C_E}}{l-1} \times (i-1) \right]}{\sum_{i=1}^{l} \mu_{d_i}(C_E)}. \quad (28)$$

The proposed model was applied for the case of three possible options. The first two options are the manufacture of wall products based on crushed rubble and screenings obtained from processing construction scrap. The practical value lies in reducing expensive Portland cement in the composition of building solutions and mixtures. The first two options correspond to the circular model, the waste of one process becomes resources for another [29, 30]. Therefore, these options are selected for comparison. The third option considers the use of ordinary wall products made of aerated concrete without the use of waste.

Option 1 – wall products are made of non-autoclaved aerated concrete [6].

Option 2 – production of wall blocks from polystyrene concrete.

Option 3 – wall blocks made of aerated concrete.

For the practical calculation of a wall using construction waste, the ecological-economic effect will be determined as low – 0.1, below average – 0.25, average – 0.5, above average – 0.75 and high – 1. Defuzzification, according to formula (28), gives the estimated prediction of the ecological and economic efficiency:

for the first option

$$C_{E1} = \frac{0.25 \times 0.1 + 0.29 \times 0.25 + 0.35 \times 0.5 + 0.42 \times 0.75 + 0.54 \times 1}{0.25 + 0.29 + 0.35 + 0.42 + 0.54} = 0.609;$$

for the second option

$$C_{E2} = \frac{0.25 \times 0.1 + 0.24 \times 0.25 + 0.44 \times 0.5 + 0.35 \times 0.75 + 0.45 \times 1}{0.25 + 0.24 + 0.44 + 0.35 + 0.45} = 0.588;$$

for the third option

$$C_{E3} = \frac{0.55 \times 0.1 + 0.66 \times 0.25 + 0.65 \times 0.5 + 0.25 \times 0.75 + 0.25 \times 1}{0.55 + 0.66 + 0.65 + 0.25 + 0.25} = 0.416.$$

The first option is the most appropriate.

5. DISCUSSION OF THE RESULTS

The use of secondary materials in the form of products of the construction and demolition waste of real estate objects for the production of raw components of building mixtures is one of the promising directions of resource-saving technological solutions that will contribute to the reduction of the development of natural mining raw materials, the reduction of the area for the placement of dumps for the temporary storage of such waste. It will also contribute to reducing harmful loads from artificial products on the environment. The proposed model improves and takes into account the requirements of circular business models [30, 32]. The main provisions of circular business models are rethinking the role of waste as a resource, contributing to the improvement of the environmental situation.

The proposed technique allows changing the values of universal sets characterising environmental parameters, socio-economic parameters and engineering-technological solutions (Fig. 3) to regulate the obtaining of ecological-economic effects from waste. The final result of the developed method differs from the method (The PLS-SEM Model) of assessing the influence of factors on waste generation. The PLS-SEM Model is to identify the level of significance of each group of factors in contributing to construction waste [33, 34]. The model based on the theory of fuzzy sets can be used when comparing options for the use of different wastes and allows choosing the most optimal option based on the indicator of ecological and economic efficiency.

7. CONCLUSIONS

1. The proposed fuzzy inference model aimed to manage the use of waste in wall manufacture allows the combination of quantitative and qualitative influence factors, which could be helpful to evaluate such comprehensive criterion as ecological and economic efficiency *E* at the predesign stage of construction in a clear, comparable form.
2. The modelling results show that using construction and demolition waste for wall erection made of non-autoclaved aerated concrete has a slight domination of production wall blocks from polystyrene concrete – 0.609 and 0.588 points, respectively. The last alternative (wall blocks made of aerated concrete) gains the lowest ecological and economic efficiency value – 0.416 points.
3. The reliability of the predicted values of the ecological and economic efficiency of production obtained by the proposed methodology for specific linguistic variables indicates the sufficiently high practical significance of the expert modelling system for making organisational and technological decisions. Nevertheless, further steps to validate the model are obligatory for real case practice implementation.
4. The developed technique allows the use of construction waste in construction at the design stage, depending on the type of waste, available technologies and local regulations.
5. Additional research should be conducted in this area to optimize the life cycle management of construction materials, including their production, use, recycling and secondary use, in order to maximize their durability and reduce waste. It is worth investigating waste management on the total cost of construction.

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