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Machine Learning (*ML*) Methods in Assessing the Intensity of Damage Caused by High-Energy Mining Tremors in Traditional Development of *LGOM* Mining Area

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Abstract: The paper presents a comparative analysis of Machine Learning (*ML*) research methods allowing to assess the risk of mining damage occurring in traditional masonry buildings located in the mining area of Legnica-Głogów Copper District (*LGOM*) as a result of intense mining tremors. The database of reports on damage that occurred after the tremors of 20 February 2002, 16 May 2004 and 21 May 2006 formed the basis for the analysis.

Based on these data, classification models were created using the Probabilistic Neural Network (*PNN*) and the Support Vector Machine (*SVM*) method.

The results of previous research studies allowed to include structural and geometric features of buildings,as well as protective measures against mining tremors in the model. The probabilistic notation of the model makes it possible to effectively assess the probability of damage in the analysis of large groups of building structures located in the area of paraseismic impacts. The results of the conducted analyses confirm the thesis that the proposed methodology may allow to estimate, with the appropriate probability, the financial outlays that the mining plant should secure for the repair of the expected damage to the traditional development of the *LGOM* mining area.

Keywords: mining damage, housing construction, compensation, damage risk, Machine Learning

1. Introduction

Underground mining adversely affects the surface and building structures by disturbing the balance of the rock mass. Mining tremors are the dominant type of mining impacts on the development of the Legnica-Głogów Copper District (*LGOM*). They occur as a result of sudden displacement, collapse or fracture of the rock layers [1]. This is related to the release of energy, which poses a threat both to mining excavations in the underground part of the mine and to objects located on the surface (e.g. [2]–[5]).

The occurrence of mining tremors in the *LGOM* area is caused by both natural and technological factors related to the method of extracting copper ore deposits. Limestone, sandstone and anhydrite rocks lying above copper ore deposits have the ability to accumulate elastic energy, releasing it during rock mass fracture. Another factor conducive to the accumulation of energy is the considerable depth of mining, ranging from 600 to over 1000 m [5],[6].

In 2002-2006, several high-energy mining tremors occurred in the *LGOM*. In the town of Polkowice, the three most intense ones occurred:

- on 20 February 2002 (tremor energy 1.5×10^9 J),
- on 16 May 2004 (tremor energy 8.4×10^8 J) and
- on 21 May 2006 (tremor energy 1.9×10^9 J).

After their occurrence, a large number of mining damage claims were recorded among traditional buildings in Polkowice . The analysis covered a group of 256 single-family buildings of traditional brick construction, erected between 1980 and 2002 in three housing estates.

The location of epicentres of the tremors in relation to the analysed development is illustrated in Figure 1.

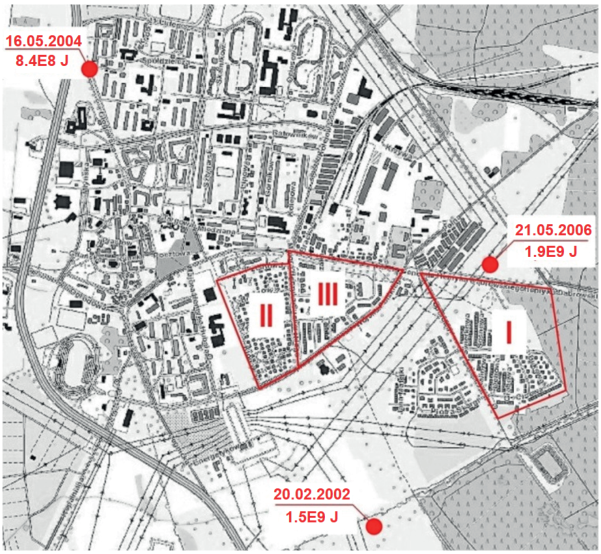


Fig. 1. Location of epicentres of high-energy mining tremors and analysed development. *Source:* [7]

The preliminary analysis of the database [8] allowed to select those features of the analysed structures that were related to the mining damage to the building as a result of a mining tremor.

In this way, a monolithic database was obtained, which made it possible to collect all the objects in a common set, ignoring the division into individual estates.

Therefore, the conducted research aimed at creating classification models to assess mining impacts in the form of high-energy mining tremors on the intensity of damage to traditional development in the *LGOM* mining area.

In order to conduct a comparative analysis, the preliminary research was based on the structure of the reported mining damage [8],[9]. This article, which is a continuation of previous analyses, presents the results of research testing whether the use of the damage intensity index (w_u), in the case of high-energy mining tremors, will enable a more accurate assessment of the extent of damage compared to the information contained in the reports. For this purpose, the Support Vector Machine (*SVM*) method was used in a classification approach. In addition, the *K-means* method was applied as a supporting analysis, which enabled the optimal categories of w_u indices to be extracted, contributing to an increased level of accuracy of the model.

2. Research methodology

2.1. Probabilistic Neural Network (*PNN*)

Artificial neural networks are universal tools for multidimensional regression of problems and classification [10]. The advantage of *PNN*, unlike other artificial neural networks (e.g. *MLP* – Multilayer Perceptron or *RBF* – Radial Basis Function), is the possibility of interpreting its structure as a conditional probability density distribution for a decision variable. The process of building *PNN* networks is also different when compared to multilayer perceptron networks. Due to the lack of weights on synaptic connections, it does not require learning that is typical for most other feedforward networks (data diodes) (e.g. [10]-[11]). During the network simulation, when projecting a given input of vector *X*, the "weighing" role is played by the *Gaussian* kernel functions, which are located on the palette of training patterns [12].

There are four computational layers in *PNN* (see Fig. 2): an input layer, a pattern layer, a summation layer and a decision layer (e.g. [10]).

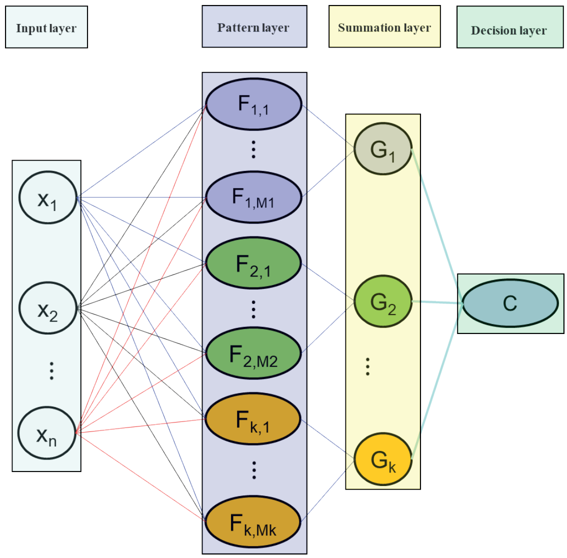


Fig. 2. Structure of probabilistic neural network *PNN*. *Source:* [10]

In the input layer, a given signal is introduced into the network in the form of a multidimensional vector $X = (x_1,...,x_n)^T \in R^n$. In the next layer, for the vector X given at the input, the signals are recognised in relation to the kernel function $F_{ki}(X)$. These functions constitute cluster areas for data patterns of categories divided into $k = 1..K$ groups and corresponding to individual categories of the decision variable (at the network output). Thus, the activation value of individual kernel functions is obtained [11]. The individual kernel functions are *Gaussian* curves written in the following form:

$$F_{ki}(X) = \frac{1}{(2\pi\sigma)^{n/2}} exp\left(\frac{-\|X-X_{ki}\|^2}{\sigma^2}\right) \quad (1)$$

σ – width (fuzzy parameter) of the kernel function,

$X_{ki} \in R^n$ – pattern in the input space constituting the centre of the kernel function F_{ki}.

In the summation layer, for each separated subgroup of pattern neurons representing K different categories within a given category ($k = 1..K$), all activated kernel functions are aggregated, the course of which can be written in the following form [11]:

$$G_k(X) = \sum_{i=1}^{M_k} w_{ki} F_{ki}(X) k \in \{1, \ldots, K\} \quad (2)$$

M_k – number of neurons from the pattern layer assigned to recognise k-th category,

w_{ki} – weights meeting the assumption $\sum_{i=1}^{M_k} w_{ki} = 1$.

As a result of comparing the G_k values calculated in the summation layer and selecting the k category for which G_k has the highest value, the result of the pattern X classification is obtained (e.g. [12]-[13]):

$$C(X) = argmax_{l \le k \le K}(G_k) \quad (3)$$

It was possible to make the obtained classification result more detailed by the probability level based on the information contained in the third (summation) layer, which stores the levels of activation of the kernel functions for individual categories. Due to the fact that these functions are *Gaussian* functions, the resultant value of this activation can be equated with the risk measure of mining damage occurrence in probabilistic notation.

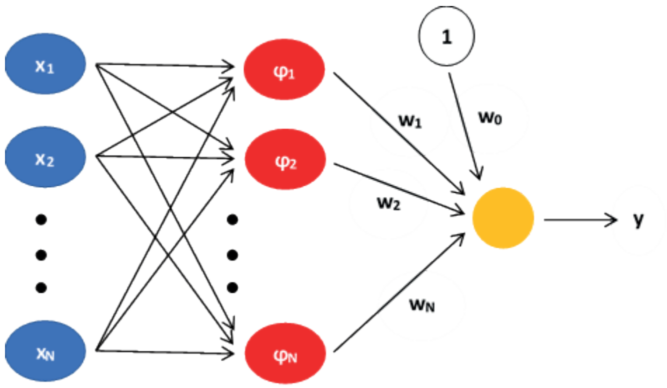
2.2. Support Vector Machine method (*SVM*) in classification approach

SVM networks, also known as the *Support Vector Machine* method, belong to the group of feedforward networks with a two-layer structure (consisting of a hidden layer and an output layer) that can use different types of activation functions (linear, polynomial, radial and sigmoid) [10].

The inspiration for the creation of the method, the origins of which date back to the 1970s [14], was the idea of separating classes by means of a linear decision boundary (hyperplane), the location of which would be optimal for the observed learning sample.

In 1998, *Vapnik* [15], striving to eliminate the imperfections of *MLP* (Multilayer Perceptron) and *RBF* (Radial Basis Function) neural networks, using error function minimisation in learning, presented a new approach in terms of network construction and learning.

The essence of the *SVM* operation in terms of classification, the structure of which is illustrated in Figure 3 [10], is the presentation of learning as a weight selection process that maximises the so-called margin of separation that separates different classes in the data space.



w_0 – weight introducing the component of the constant function shift.

Fig. 3. Basic structure of a nonlinear *SVM* network. *Source:* [10]

The supporting vector method performs classification tasks for both continuous and categorised variables, which construct optimal hyperplanes in a multidimensional space separating data belonging to different classes with a maximum margin of separation [10].

The main problem related to the construction of the *SVM* classification network is the appropriate selection of parameters: C – which is a regularisation constant occurring in the loss function and conditioning the learning process (e.g. [16]) and γ – which determines the bandwidth of the adopted kernel functions. Determination of the optimal values of these parameters is performed with the use of the gradientless optimisation method of *pattern search* [17].

In the case of the classification of non-linearly separable data, the commonly used solution is the use of the *Cover's* theorem (e.g. [10], [18]). It consists in projecting the original x patterns from the primary space (N) into another functional space – the feature space (K), with a higher dimension ($K \geq N$), in which the patterns are linearly separable. The feature space, defined by means of radial functions, into which the inseparable linear data in the primary space has been transformed, is represented by Formula:

$$\varphi(x) = exp\left(\frac{-\|(x-c)\|^2}{\gamma^2}\right) \tag{4}$$

γ – radial function bandwidth,

c – radial function centres,

x – input pattern vector.

As a result of the performed transformation, the equation of the hyperplane in the feature space is described by Formula [10]:

$$y(x) = w^T\varphi(x) + b = \sum_{j=1}^{K} \omega_j\varphi_j(x) + b = 0 \tag{5}$$

w^T – weights vector,

b – polarisation weight,

$\varphi(\cdot):R^n \rightarrow R^n{}_h$ – transformation transforming the original input data into the feature space,

ω_j – j-th weight between the neuron in the hidden layer and the output neuron.

At the points closest to the hyperplane, defining its course, but at the same time the most difficult to classify, the support vectors will be created (see Fig. 4).

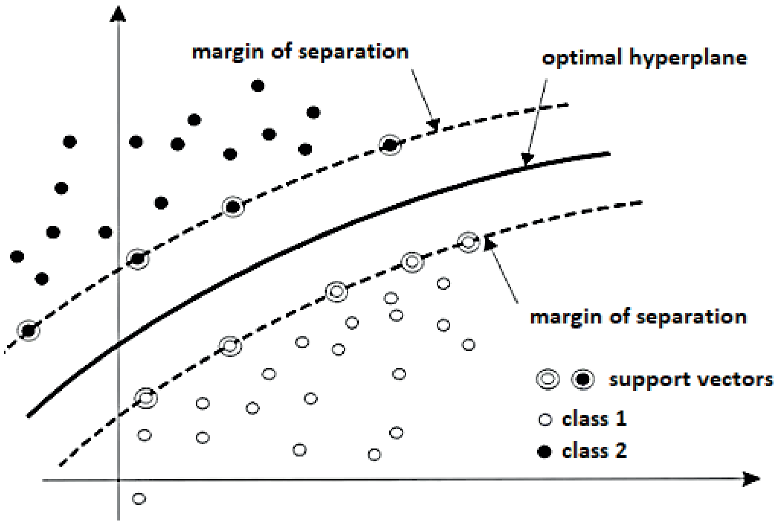


Fig. 4. Optimal hyperplane with maximum margin of separation. *Source:* [19]

Learning the *SVM* nonlinear network consists in determining the value of the weight vector w, so that for non-linearly separable variables the classifying hyperplane that minimises the assumed error function is determined while maintaining the margin of separation of the maximisation condition. In this process, depending on the value of the *C* regularisation constant, the network complexity is reduced [10], [19].

The kernel function $K(x, x_i)$ can be used in a nonlinear *SVM* network if it satisfies the *Mercer* condition [15],[16]. This theorem answers the question whether the analysed kernel function can be presented in the form of two unspecified vector functions $\varphi(x)$ and $\varphi(x_i)$, and whether the symmetrical continuous function $K(x, x_i)$ is expandable into a series:

$$K(x, x_i) = \sum_{i=1}^{\infty} \lambda_i \varphi(x) \varphi_i(x_i) \quad (6)$$

$\varphi(x)$, $\varphi_i(x_i)$ – vector functions,

λ_i – non-negative complementary variable.

Examples of the kernel functions meeting the assumed *Mercer* condition are presented in Table 1.

Table 1. Examples of kernel functions. *Source:* [10]

Kernel type	Equation	Remarks
Linear	$K(x, x_i) = x^T x + \gamma$	γ – any
Polynomial	$K(x, x_i) = (x^T x + \gamma)^p$	p – polynomial degree
Radial	$K(x, x_i) = exp\left(\frac{-1}{\gamma}\|x - x_i\|^2\right)$	γ – common to all kernels
Sigmoid	$K(x, x_i) = tgh(\beta_1 x^T x_i + \beta_0)$	Constraints on β_0 and β_1

Ultimately, the output of the nonlinear *SVM* network depends on the kernel function $K(x, x_i)$ and is defined as:

$$y(x) = w^T \varphi(x) + b = \sum_{i=1}^{N_{sv}} \propto_i d_i K(x, x_i) + b \tag{7}$$

N_{sv} – number of support vectors xi,

α_i – *Lagrange* multiplier,

d_i – pattern value,

$K(x,x_i)$ – kernel function.

2.3. *K-means* method

In addition to Machine Learning (*ML*) methods, the *k-means* clustering method was also used. It was aimed at indicating the optimal categorisation of the variables determining the value of the damage intensity index (w_u) and the standardised amount of compensation paid for mining damage (*kwt*) to the modelling stage.

For this technique, it is necessary to pre-define the parameter *k,* which determines the number of subgroups that will be separated from the data set. The similarity in a given cluster should be as large as possible, and separate groups should differ as much as possible from each other. The selection of the initial locations of the centres of clusters is made arbitrarily or randomly. In the next steps, adjustments are made by repeating the method with different values of the *k* parameter and evaluating the means for a particular cluster in each analysed dimension. The algorithm of the method, consisting in transferring objects between clusters, lasts until the variability within clusters is minimised and it is maximised between clusters [20].

3. Mining damage risk assessment model – *PNN*

The database containing the reported damage to single-family housing estates in the town of Polkowice formed the basis for the creation of the model for the assessment of the risk of mining damage. The damage was the consequence of high-energy mining tremors of 20 February 2002, 16 May 2004 and 21 May 2006.

Two *PNN*s were created with the use of *MATLAB* [17]. For building the optimal network structure, it was essential to determine the value of the parameter σ defining the bandwidth of the *Gaussian* kernel function, adopted in an arbitrary manner [12]. For the created networks, the values of the σ parameters were selected by means of gradual adjustments resulting in obtaining the highest classification accuracy for the training and test sets and the smallest difference between them, thus guaranteeing high generalisation properties. As it was mentioned in Chapter 2.1, this network allows for a probabilistic interpretation of the obtained result, understood as the risk of mining damage. Determining the probability for the results of *PNN* network classification consists in averaging the values of activated Gaussian kernels occurring in the penultimate layer of the network [12],[13].

Reports after the first and, in total, after all tremors were analysed, and the number of the analysed cases was 222 and 284, respectively. The variables describing the technical, construction and material features of the studied development included: development type, building projection and building shape (they were determined in accordance with the *Guideline* [21]), foundation or basement wall structure, aboveground load-bearing wall structure, ceiling structure and differentiation of ceiling levels within individual storeys, protection against paraseismic effects. The set of these features acted as input data for the created models. The data was divided into sets: the training set and the test set – used to evaluate the generalisation properties of the *PNN* network model (e.g. [10], [13]). The classification accuracy for such a network, both for the training set and the test set, reached the level of 70÷75% of correctly classified cases.

In order to demonstrate how the *PNN* network works in the mining damage risk assessment and in making the obtained classification results more detailed by the corresponding probability values, simulations of the created models were carried out, generating 768 sets of variables evenly distributed in the input space. The number of the cases resulted from the combination of representative states (values) of all analysed variables. In this way, the considered space of input variables was fully covered.

The results of the performed simulations, which were the mean of the obtained probabilities of mining damage for the individual values of the variables included in the model simulation, are presented in Table 2.

Table 2. Mining damage probability values for individual variables included in *PNN* model. *Source:* [9]

Variable	Variable status	Probability of mining damage after one high-energy tremor	Probability of mining damage after three high-energy tremors
Development type	Detached	0.115	0.314
	Terraced	0.165	0.370
Building shape	simple, compact	0.076	0.268
	simple, elongated	0.114	0.337
	poorly fragmented, compact	0.147	0.340
	poorly fragmented, elongated	0.162	0.362
	highly fragmented, compact	0.152	0.338
	highly fragmented, elongated	0.179	0.405
Foundation/Basement wall structure	concrete monolithic	0.116	0.325
	concrete blocks	0.161	0.359
Overground load-bearing wall structure	slag concrete blocks	0.060	0.209
	concrete blocks	0.217	0.473
Ceiling structure	monolithic reinforced concrete slab	0.128	0.292
	prefabricated slabs	0.149	0.392
Various ceiling levels	Constant	0.105	0.321
	Variable	0.169	0.359
Protected against paraseismic effects	No	0.163	0.358
	Yes	0.113	0.327

The presented results allow to draw a conclusion that there is a tendency of an increase in the risk of mining damage occurrence with the occurrence of successive high-energy mining tremors. The lack of clear relationship between the technical, construction as well as material features of the tested development and the increased risk of damage in the years 2002-2006, is noticeable. This is most likely due to the uncertain nature of the collected research material, based on reports resulting from subjective reactions of building owners or users reporting the occurrence of damage.

In order to illustrate the potential use of the created networks, an exemplary variant analysis was carried out, consisting in simulating the operation of the network for three buildings with different technical features and subject to a high-energy mining tremor. The results are presented in Table 3.

Table 3. Exemplary use of *PNN* to assess risk of mining damage in a single building with a given structure. *Source:* own study

Variable	Building I	Building II	Building III
	Variable value		
Development type	detached	Detached	terraced
Building shape	simple, compact	poorly fragmented, compact	highly fragmented, elongated
Foundation/Basement walls	concrete monolithic	concrete monolithic	concrete blocks
Overground load-bearing walls	slag concrete blocks	concrete blocks	concrete blocks
Ceilings	monolithic reinforced concrete slab	prefabricated slabs	monolithic reinforced concrete slab
Various support level of ceilings	variable	Constant	constant
Protected against paraseismic effects	yes	No	no
Risk of mining damage:	0.48	0.63	0.69

The obtained results depend on the variables indicating the analysed features of buildings. As a result, the risk of mining damage was obtained that occurred in a building with given technical properties after a tremor with energy level falling within the values of the seismic phenomena analysed in the study.

4. *SVM* network in assessing the extent of damage intensity

Further research was carried out to verify the effectiveness of using the damage intensity index w_u (e.g. [22],[23]). It was checked whether in the case of high-energy mining tremors, the use of the damage intensity index allowed for a more accurate assessment of their extent as compared to the information contained in the reports. The decision was made that the *SVM* method would be used. The main advantage of this method, unlike typical artificial neural networks, is the uniqueness of the model building process and the high level of generalisation of the acquired knowledge [10]. Then, a comparative analysis of the created *SVM* model was carried out with the *PNN* network, in the description of which the damage intensity index (w_u) was not used.

The next stage of the research involved the determination of the optimal division of the value of the building damage intensity index (w_u) in relations to the uniform compensation amounts (*kwt*) into categories (w_{usk}). For this purpose, the *k-means* method, belonging to the group of cluster analysis algorithms (e.g. [20]), was used.

The method's algorithm involves moving objects between clusters. It is executed until the variability within clusters is minimised, and between clusters is maximised.

As a result of the above analysis regarding the value of the building damage intensity index (w_u), four categories were distinguished. The obtained values of statistics and the division of variables resulting from the conducted *k-means* cluster analysis are presented in Table 4 and Figure 5.

Table 4. Results of *k-means* cluster analysis for building damage intensity index (w_u) and uniform amount of compensation for mining damage (*kwt*). *Source:* own study

Cluster	Statistics	Variables	
		w_u	*kwt* [PLN]
I	Mean	4.88	992
	standard deviation	1.27	446
II	Mean	9.75	1777
	standard deviation	1.56	506
III	Mean	16.03	5497
	standard deviation	1.08	726
IV	Mean	20.42	8232
	standard deviation	1.04	211

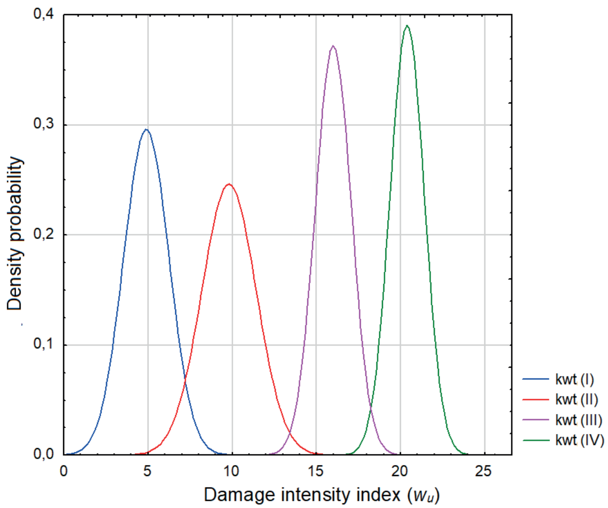


Fig. 5. Division of the building damage intensity index (w_u) by the *k-means* method in relation to the uniform amount of compensation for mining damage (*kwt*). *Source:* own study

As a result of the research, the results were obtained that indicated the optimal divisions of the variables for further analysis. This allowed to introduce the following grading for the w_{usk} variable (degrees of intensity of generalised building damage index):

- 0, when $w_u = 0$,
- 1, when $w_u = (0; 5>$,
- 2, when $w_u = (5; 10>$,
- 3, when $w_u = (10; 15>$,
- 4, when $w_u = (15; 20>$,
- 5, when $w_u > 20$.

For the construction of the *SVM* classification network model after all three high-energy mining tremors, categorised building damage intensity indices (w_{usk}), structural and geometric features of the analysed development, as well as the protection against mining tremors or lack of it, were adopted as variables. The data set was divided into the training set and the test set, and the total number of the analysed cases was 516. The variables adopted for the analysis together with their division are demonstrated in Table 5.

Table 5. Variables included in classification model of *SVM* network. *Source:* own study

Variable	Code	Variable division
Categorical dependent variable		
Building damage intensity index categories	w_{usk}	0, when w_u = 0, 1, when w_u = (0;5>, 2, when w_u = (5;10>, 3, when w_u = (10;15>, 4, when w_u = (15;20>, 5, when w_u > 20.
Categorical input variable		
Development type	r_z	1 – detached and semi-detached, 2 – terraced.
Projection and building shapes	k_s	1 – straight or weakly segmented, compact, 2 – straight or weakly segmented, elongated 3 – strongly disjointed, compact, 4 – strongly disarticulated, elongated.
Basement or foundation wall structure	s_p	1 – made of concrete blocks, 2 – monolithic concrete.
Overground load-bearing wall structure	s_w	1 – from hollow blocks of slag concrete, 2 – from cellular concrete blocks.
Ceiling structure	s_t	1 – slab, prefabricated, 2 – monolithic reinforced concrete.
Various support level of ceilings in a storey	z_p	1 – none, 2 – present.
Protection against paraseismic effects	t_r	1 – none, 2 – present.

In accordance with the adopted methodology (Chapter 2.2), the parameters C and γ, which condition the final shape of the *SVM* network structure, were determined as a result of pattern search (*PS*) optimisation in the *MATLAB* environment [17].

The summary of the basic characteristics of the created *SVM* classification network model and the results of the simulations are presented in Table 6.

Table 6. Characteristics and validity of *SVM* classification model to assess intensity category of building damage intensity index w_{usk}. *Source:* own study

	Kernel type	Parameter C	Kernel function γ bandwidth	Number of support vectors	Classification accuracy	
					Learning sample (70%)	Test sample (30%)
Model parameters	*RBF*	1.0	0.25	121	80.1%	74.8%

The presented results point to a noticeable reduction in the number of support vectors, constituting the core of the *SVM* network structure, in relation to the number of patterns in the training set – c.f. Table 6. This reduction, when compared to the original number of learning patterns, from 361 to 121, proves good generalisation properties of the constructed model. The obtained levels of accurate classifications of the created model, both for the training set and the test set, reached the values of 75÷80% of correctly classified cases.

As a result of the applied categorisation of the intensity of damage observed in the object based on the k-means method, the classification level was about 5% better than that of a probabilistic *PNN* neural network based on subjective reports of building owners reporting the fact of damage, analysed in Chapter 3.

5. Summary

The results of the conducted analyses demonstrate that the created model of the *SVM* classification network, when compared to the probabilistic *PNN* neural network, allows for a more precise determination of the extent of potential damage in the analysis of large groups of buildings located in the area of paraseismic interactions. This is due to the change in the original form of the damage description and the use of the optimal categorisation of the damage intensity index (w_u). Therefore, it can be concluded that the integration of the *SVM* and *k-means* methods is more effective for describing the risk of damage to buildings located in the area of intense mining tremors.

Therefore, it has been proved that carrying out a detailed inspection of the technical condition of buildings using the damage intensity index (w_u) after the occurrence of a high-energy mining tremor allows for a more precise determination of the extent of potential damage to building structures than in the case of data resulting from subjective reports of their owners or users reporting the occurrence of damage.

The presented results of the analyses should be treated as an assessment of the phenomenon on a global scale. Determining the influence of mining effects on a specific building requires an individual assessment of the picture and causes of damage, and often a detailed numerical analysis is necessary there as well.

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Environmental aspects of the production and use of autoclaved aerated concrete with low density

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Abstract: The purpose of the article is to investigate the state of carbon dioxide emissions generated as a result of wall materials production and the construction industry as a whole. The paper provides a comparative analysis of housing construction in Ukraine and in some CIS countries. Against the background of the indicators of low housing availability and low relative volumes of housing construction, the issue of high energy consumption remains valid. The absolute and relative volumes of greenhouse gas emissions from economic activity of the population of Ukraine are given. The projected consequences for Ukraine from continued CO_2 emissions on the same level and temperature rise are estimated. It is deemed that the most suitable wall material for countries with emerging economies is autoclaved aerated concrete (AAC); since it is a structural and thermal insulating material, it can solve the problem of housing construction.

The paper shows the key priority of low energy consumption and makes emphasis on lowering the density of the produced aerated concrete, reducing mineral additives and cement production expenses.

Keywords: greenhouse gases, energy saving, construction, autoclaved aerated concrete, low density

1. Introduction

The construction industry continues to be the largest consumer of energy and fresh water in the world. It is also responsible for producing 40% of global greenhouse gas emissions. Being a fund-forming industry, construction is directly related to energy consumption and greenhouse gas emissions levels. The energy consumption of buildings depends greatly on the wall enclosure. Today, autoclaved aerated concrete (AAC) has replaced traditional wall materials from the construction market, such as ceramic bricks, silica bricks and claycrete. The main reason for this is because they are energy-intensive in production and not energy-efficient at the stage of operation. Its share in wall materials in European countries is 40-60% and 53% in Ukraine.

A classic example of the formation of the AAC production industry is the experience of China and Poland. Back in 1947, Poland bought the technology and part of the equipment from the Swedish company "Siporex" with the right to replicate the equipment. As a result, its production capacity increased to 5-7 million m^3 of AAC per year. At the end of the 1950s 10 plants were sold to the former Soviet Union and 7 plants to the former Czechoslovakia. China has 2,300 plants, most of them were built by China itself, with a total production capacity of 220 million m^3/year. They also export their plants to other countries around the world.

The analytical agency for market research [1], which brings together professionals in global market information and includes 1,700 research groups from 81 countries, has presented its forecast for the growth of the AAC global market. According to this forecast, the AAC global market will grow from 18.8 billion USD in 2020 to 25.2 billion USD by 2025 at an average annual growth rate of 6.0% during 2020-2025.

Many years of experience in AAC production have shown that the energy cost for its production is 320 kWh/m^3, while it requires 900 kWh/m^3 to produce dense bricks, and 600 kWh/m^3 for hollow bricks [2].

Ukrainian construction industry is facing several major challenges, such as:

- increasing the relative volumes of housing construction from 0.22 m^2/person per year to the level of international standards – about 1 m^2/person per year;
- insulating the existing housing stock built in 1960-1980s with low thermal resistance of envelopes;
- switching to construction of energy efficient buildings using modern energy efficient wall materials;
- achieving a significant increase in the use of alternative energy sources;
- reducing greenhouse gas emissions through the rational use of hydrocarbons and new technologies for their utilization.

Due to low energy efficiency of production, according to the Ministry of Economy of Ukraine, the country's financial losses in 2018 amounted to almost 1.5 billion USD. According to [3] Ukraine has a huge potential for energy savings in the housing sector (34%), production sector (28%) and in the energy transformation sector of thermal power plants (21%). Service industry and agriculture make up 12% and 4% of the energy saving potential, respectively.

According to the Energodata annual global research, the level of energy intensity of the gross domestic product of Ukraine twice exceeds the average number throughout the world . In particular, for example, in Poland this indicator is 2.5 times lower than in Ukraine; in Germany it is 3.3 times lower. The enclosing structures of the outer walls of residential buildings from 1960s – 1980s were built mainly from claydite concrete in the form of ceramic and silicate wall panels, and bricks with a density of 1400-1900 kg/m^3. Nowadays in Ukraine 1.5 times more energy is used to heat a unit area than in the U.S., and about 3 times more than in Sweden.

Energy saving should be considered not only in terms of economic losses, but it can also help reduce greenhouse gas emissions from the combustion of fossil hydrocarbons. According to the Kyoto Protocol, 6 gases are considered greenhouse gases: carbon dioxide, methane, nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride (SF_6). Of these 6 gases, 3 are of paramount importance, and they are closely related to human activities.

In 2015, 197 nations signed the Paris Agreement on reducing greenhouse gas emissions, committing to prevent an average air temperature increase of 2°C by the end of the century. This requires adapting the power economy, construction sector, manufacturing industry, agriculture, and the entire economy to reduce CO_2 emissions. The International Monetary Fund insists that taxation of CO_2 emissions is the most effective tool for limiting the use of fossil fuels and related CO_2 emissions.

Environmental problems and climate change are now dominant for the development of civilization. The state of the construction complex (housing construction, production of building materials, insulation and maintenance of the housing stock) largely reflects the efficiency of the rational use of fossil hydrocarbons and greenhouse gas emissions.

2. Environmental problems

Environmental problems and climate change remain a huge concern for humankind. According to expert forecasts, climate change in Ukraine can cause a decrease in agricultural yields up to 30% in the nearest future and will likely cause other cataclysms. Catastrophic storms, extreme heat and life-threatening pollution are possible.

According to NASA and the National Oceanic and Atmospheric Administration (NOAA), 2019 was the second hottest year on record. Every decade since the 1960s has been warmer than the decade before with the past decade being the warmest on record [4]. According to the 2018 Global Emissions Gap Report, 55.3 gigatons of greenhouse gasses were emitted into the atmosphere, compared to 53.5 gigatons in 2017. If these carbon dioxide emission trends remain, by the end of this century the Earth's temperature will rise by 3.2 °C and will bring devastating consequences for the entire planet. The European Parliament calls on the EU to submit a strategy for achieving climate neutrality to the UN Convention on Climate Change as soon as possible, but no later than 2050. MEPs call on the European Commission to include a 55% greenhouse gas emission reduction target to the European Green Deal by year 2030.

As can be seen from Fig. 1, the average rate of temperature increase has changed significantly since 1981. Land and ocean temperatures have risen at an average rate of + 0.13 °F or + 0.07 °C each year.

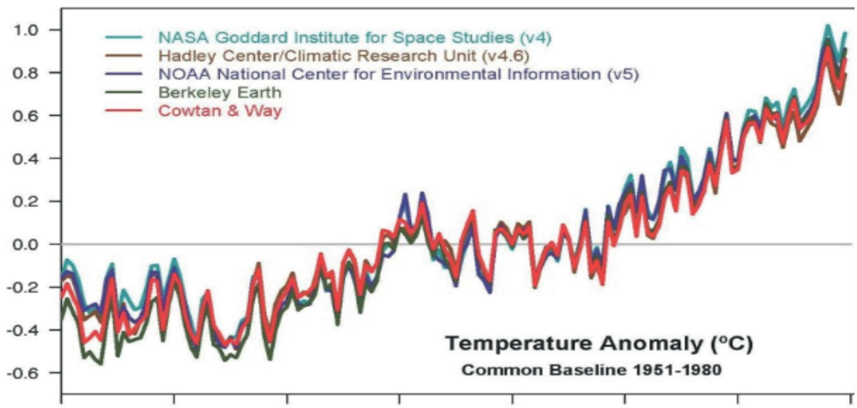

Fig. 1. Average annual changes in the average global temperature of the Earth. *Source*: [21]

The main sources of carbon dioxide formation are shown on fig.2. The main pollutants of the atmosphere are thermal power plants (TPP), transport vehicles, manufacturing industry, housing and communal services. TPPs only produce more than 30% of all emissions [5].

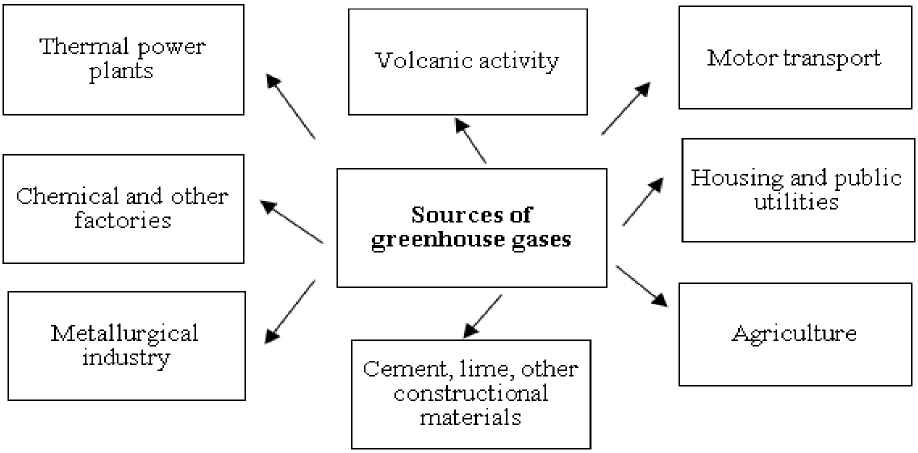

Fig. 2. Main sources of carbon dioxide emissions. *Source*: own study

The functioning of the fund-forming construction industry is provided by cement, metallurgical, chemical and other enterprises of the building materials industry, transport and enterprises in the energy sector of the economy. According to the latest IEA data, global cement production causes 10% of total CO_2 emissions.

Energy consumption and greenhouse gas emissions are associated with the maintenance of housing and other industrial and public facilities. The world's biggest energy consumers are buildings (31%), industry (29%) and transportation (29%). The rest of 11% of the world's energy consumption is shared between other fields.

Table 1 shows coefficients of CO_2 emissions from combustion of different fuels for a detailed estimation of emissions. The carbon tax depends on the type of hydrocarbons and their carbon content. The CO_2 emissions tax was first introduced in Ukraine in 2011. Its rate was purely symbolic (from 0,0086 EUR to 0,014 EUR per ton of CO_2 emissions). Since January 1, 2019 the tax rate has increased 24,4 times up to 0.33 EUR per one ton of CO_2 emissions. Meanwhile, the EU countries have high taxes on carbon dioxide emissions. On average, this tax is 50 euros per ton of CO_2 emissions. However, Ukraine plans to gradually increase the ecological tax on CO_2 by 2024. This tax should be paid by those economic entities where the total annual volume of CO_2 emissions exceeds 500 tons.

Carbon taxes have a significant impact on reducing greenhouse gas emissions with their high rate and long lead times. Canada plans to raise the charge per ton of greenhouse gas emissions to 170 USD (150 EUR) by 2030 and to achieve zero greenhouse gas emissions by 2050. This was announced by the Prime Minister at the 2021 Climate Summit in Glasgow.

Table 1. Coefficients for calculating CO_2 emissions from fuel combustion

Type of fuel	CO_2 emissions
Natural gas	1,85 tons of CO_2 / (thousand m^3)
Coal	2,7–2,8 tons of CO_2 per ton (depending on the grade of coal)
Peat	~1,5 tons of CO_2 per ton, one ton of peat gives ~2 times less energy than a ton of coal
Motor spirit Furnace oil Diesel fuel Aviation kerosene	3,0 tons of CO_2 per ton or 2,1–2,3 kg CO_2 per litre depending on the temperature of the fuel and its brand (summer fuel is more dense, and winter fuel is less dense)
Fuel wood and agricultural waste	CO_2 emissions are considered to be zero, since CO_2 released into the air during combustion was previously absorbed from the atmosphere during plant growth (a closed cycle is formed that does not lead to an increase in CO_2 concentration in the atmosphere)

As seen in Table 1, it is preferable to use wood fuel and natural gas, which minimize carbon dioxide emissions during combustion. The future of global energy is tied to renewable energy sources. The phasing out of coal, gasoline and diesel in some EU countries is part of the commitment to fight climate change.

According to the European Commission's research center, Ukraine continued to reduce its CO_2 emissions in 2019. They amounted to 196 million tons, for comparison, in 2018 emissions were at 203 million tons, and in 1990 – 783 million tons. Ukraine's per capita emissions have also decreased. Last year in 2020, they were nearly 4.5 tons per year, down from 4.6 tons a year earlier and more than 15 tons in 1990. The average global emissions per capita are 4.9 tons of CO_2.

In November 2021, at the UN climate summit COP26 in Glasgow, more than 40 countries pledged not to invest in the construction of coal-fired power plants. Coal-consuming countries, including Canada, Poland, Ukraine, Vietnam, and others, will gradually reduce using coal.

The solution to the problem of greenhouse gas emissions is essentially related to the reduction of energy consumption, primarily in the construction sector of the country through the insulation of the previously built housing stock and the construction of new buildings using energy-efficient building materials. The housing complex of Ukraine consumes about 40% of all energy used in the economy of the country. With the trend of increasing the share of construction of low-rise residential buildings in the total volume of housing construction the need for wall construction materials increases. Being an energy efficient and affordable wall material, AAC is rapidly gaining popularity and occupies the first position in the structure of wall materials.

3. Improvement of autoclaved aerated concrete production

AAC as a construction material has been known for more than 70 years in the construction market. Because of its high vapor permeability, there have been opinions about the possibility of changing the properties of the material over time with prolonged carbonation. Recent works on the examination of existing for a long time aerated concrete walls and buildings [6] and the results of other studies [7] confirmed that the process of carbonization in AAC does not bear a direct threat to the safety of buildings over a long life cycle.

An important fact is that aerated concrete combines thermal insulation and structural properties. Low-density aerated concrete allows to reduce the cost of the foundations by 30%, energy costs for heating – up to 35%, transportation costs – by 30%, the cost of housing – up to 20%. [8]. After the completion of buildings, AAC can be completely recycled for reuse (Fig. 3).

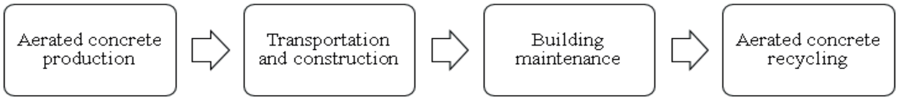

Fig. 3. Life cycle assessment of aerated concrete. *Source*: own study

Affordable materials such as sand, lime, cement and gas-forming agents are used for AAC production. Modern approaches to assess the environmental and economic effect of the production of any building material dictate the need for a comprehensive energy assessment of it at all stages of the life cycle. Of the given stages of the creation and operation of AAC (Fig. 3), the greatest energy saving effect and positive environmental consequences seem possible to obtain at the first and third stages of the life cycle of the use of this material – during the long-term operation of buildings

A comparative analysis of the energy intensity of the production of basic building materials is presented in [9]. It becomes obvious that the largest energy intensity of production falls on steel. One needs to spend 32290 MJ of thermal energy to produce 1 ton of the material; to produce 1 ton of portland cement 8 times less thermal energy is needed, 12 times less when producing bricks, 16 times less for reinforced concrete and 25 times less to produce cellular concrete

During AAC production high-energy consuming components such as cement and lime are used. Their firing temperature is respectively 1450-1500 ºC and 800-1200 ºC. According to [10] cement production takes a significant place in environmental pollution. It is characterized by the withdrawal of natural resources, atmospheric pollution, wastewater discharge, as well as the impact on the Earth's climate. Enterprises of the cement industry account for about 70% of industrial emissions of solid substances and 44% of gaseous substances.

Large reserves of cement savings in the production of AAC are brought by the right choice of silica components and active mineral additives. Under conditions of high temperature (about 200°C) and saturated steam at excessive pressure (1.2-1.4 MPa) such additives act as a component of the mineral binder. In many countries of the world, fly ash is used as a siliceous component [7][11]. As is known, the world leaders in the use of fly ash are China, Poland and Great Britain. In Ukraine, Belarus, Kazakhstan fly ash is not used, in the Russian Federation about 10% of plants are using it in AAC production.

Blast furnace granulated slag in autoclaved aerated concrete is activated by lime and cement and, in fact, acts as a mineral binder. Natural mineral additives such as rottenstone and gauze save in mineral binders [12, 13].

Zeolites, a group of minerals mainly represented by aqueous calcium and sodium aluminosilicates, may be an alternative to a part of cement in the technology of aerated concrete production. Zeolite is used as an active mineral additive in the production of Portland cement, in the manufacture of silicate bricks and dry building mixtures.

In [14] the results of study of samples containing clinker minerals and highly dispersed chalk with different ratios of components are considered. It has been proved by IR-spectroscopy methods that addition of highly dispersed chalk leads to reduction of $Ca(OH)_2$ portlandite amount in cement stone composition. In addition, it leads to the decrease of basicity of hydrosilicates of calcium. The amount of clinker minerals in the cement stone decreases, while the amount of portlandite does not decrease.

Carbonate additives increase cement hydration and create low-base calcium hydrosilicate. It is the main carrier of strength of autoclaved concrete and cement materials in general [15]. At the same time, dispersed calcium carbonate compacts the microstructure of the silicate material. When converting to the production of low-density aerated concrete, carbonate additives also act as a "protector", increasing the carbonization resistance of low-density aerated concrete.

Due to its high dispersibility, limestone fills the space between the clinker grains and improves the interaction between them by reacting chemically with the aluminate and aluminiferous phases to form calcium hydrocarbon aluminates [16].

In recent years, highly active metakaolin as a highly effective pozzolanic additive has become popular. The introduction of this additive into the composition of cellular concrete makes it possible to increase its strength at a given density. This happens due to two factors: increasing the strength of interstitial partitions by increasing the strength of cement stone and improving the pore structure of aerated concrete [17].

When the clay is fired at 650 °C, chemically bound water volatilizes and it turns into an active pozzolanic additive. Kaolinite has a wide temperature interval between dehydration and recrystallization, which greatly contributes to the formation of metakaolin, which is an additional cementitious material [18].

In contrast to the dense concrete, the use of active mineral additives of natural and man-made origin in the technology of autoclaved aerated concrete affects the water-hardness ratio of the mixture, swelling, increasing the plastic strength of the raw material and the formation of macro and microstructure of gas concrete. The aerated concrete mixture must quickly gain the plastic strength necessary to cut it into blocks. This creates certain difficulties of mass transition to the production of light autoclaved aerated concrete. The process of swelling of aerated concrete mixture itself (the end of gassing) should be balanced with the time of its setting and ensure the formation of macro pores of the correct shape. The compressive strength of the final product depends on the strength of the newly formed silicate stone and on the regularity of the macropores of the aerated concrete [19].

4. Energy Efficiency of Reducing AAC Density

The reduction of aerated concrete density while saving and increasing its strength properties remains a constant aim for manufacturers. Aerated concrete with density 300 kg/m^3 and compressive strength 2.5 MPa, as a wall construction-insulating aerated concrete is produced at the best enterprises of the industry.

Earlier wall blocks in Ukraine had an average density of 643 kg/m^3, nowadays more and more wall blocks with density 300-400 kg/m^3 are produced. The production of such blocks is less resource and energy intensive. During autoclave processing duration of product soaking can be reduced by 1,5-2 hours. This is due to a more porous structure of the aerated concrete mixture, which allows the saturated steam to penetrate deeper into the massif and warm it up faster.

Modern AAC plants operate on waste-free technology. Reducing the consumption of raw materials can be achieved by various means. For instance, the upper layer of the massif is cut off and returned to the aerated concrete mixer in the form of return sludge, as well as raw waste. The share of return sludge in the composition of the raw aerated concrete mixture can contain 16-20%.

The use of steam transfer from one autoclave to another provides a significant reduction in energy consumption during autoclave treatment of aerated concrete. The transition to the production of low-density AAC provides savings in material, energy resources and allows to get additional energy and environmental effect at production and operation stage. At the same time, this requires additional engineering and technological research to restructure the entire technological process of AAC production.

The European standard EN 771-4 [20] allows usage of the lowest class bulk density 300 kg/m^3 and operating moisture under operating conditions at 4-8%, which gives it high thermal insulation properties.

The advantages of the transition to the production of AAC with density 300 kg/m^3 and 400 kg/m^3 are quite obvious. The walling structures of domestic buildings in 1960–1980-s were built from ceramsite-concrete wall panels, ceramic and silicate bricks with density 1400-1900 kg/m^3, as well as hollow blocks, which are characterized by a high coefficient of heat transfer.

Improvement of production technology and reduction of AAC density while maintaining its performance characteristics leads to lower consumption of energy-intensive components, such as cement and lime. Due to higher vapor permeability during autoclaving, AAC with lower density heats up faster. Thus, it is possible to reduce consumption of steam (energy) for heating of aerated concrete mass and duration of autoclaving treatment.

The duration of the autoclave treatment mode after transition to the production of low-density AAC at Aeroc plants was reduced by 3 hours, and the turnover rate of the autoclave per day increased from 2.1 to 2.45 cycles. The increase in the autoclave turnover ratio provides a comprehensive effect of reducing power and gas consumption, greenhouse gas emissions and, as a result, intensifies AAC production.

Large-scale production of AAC with an average density of 500 kg/m^3 prevails in most European countries. From the websites of the companies producing AAC we can see that in each country the leading companies in terms of total production volumes and product density have been determined. The Russian Federation produces the largest quantity of AAC in Europe (13.73 million m^3), with Russian company “BONOLIT group” owning more than 20% of the AAC market with density from D200 to D600. The average AAC density in Russia is 505.7 kg/m^3. Poland ranks third in Europe with SOLBET having 30% of the market, producing aerated concrete with density D400-D700. According to the Statistics Poland Office, in 2020 5.4 million m^3 of AAC was produced. About 4 million m^3 of AAC was produced in Ukraine, being fourth in Europe in terms of total production volumes.

A special place in the European AAC market is held by the transnational concern Xella International (Germany). The “Ytong” wall aerated concrete blocks have compressive strength in the range of 2-5 MPa and average density 300-700 kg/m^3. The concern owns 95 factories with a staff of more than 7 thousand people and has a Research and Development Center which controls the quality of raw materials and technology of its factories. In 2021 Xella Russia presented the Ytong A++ aerated concrete blocks with a density rating of D300 and compressive strength of at least 2.5 MPa.

In the EU countries the heat transfer coefficient U of the outer walls is gradually reduced. In Poland after January 1, 2021 it is $U \leq 0.20$ W/m^2 K ($R \geq 5.00$ m^2 K/W). In 2021 new state standards for construction were adopted in Ukraine. According to them, the thermal resistance of building envelopes should be increased by 20% U ≤ 0.25 W/m^2 K (R ≥ 4.00 m^2 K/W). This index can be reached using D350 Ytong Energo aerated concrete blocks without additional insulation, as well as by using AAC blocks with a density of D300.

Xella International is a manufacturer of the "lightest" thermal insulation aerated concrete. For more than 15 years Ytong Multipor aerated concrete slabs with a density of 100-112 kg/m^3 have been used as insulation in many countries in Europe. This is an environmentally friendly, non-combustible, mineral-based insulation with high durability indicators. They are used to insulate buildings and two-layer masonry walls of energy-efficient buildings, and are certified for compliance with the international standard ISO 14025.

Because of the long-term economic crisis, the volume of AAC production in Ukraine decreased from 1.2 million m^3 in 1991 to 100 thousand m^3 in 2000, and has increased 40 times by 2020. The largest producers of AAC in Ukraine and Europe are "Orientir-Budellement" (32% of the market) and "Aeroc" (shares 28% of the market). Both of these manufacturers are located in the Kyiv region.

"Aeroc" was the first company in Ukraine to stop production of D600 AAC blocks. It also started mass production of energy-efficient aerated concrete with 300 and 400 kg/m^3 density and compressive strength class C2.0. The company has mastered the large-scale production of D150 insulating aerated concrete.

In 2020, the company's two plants sold 1.14 million m^3 of aerated concrete: D400 – 55%; D300 – 23%; D500 – 21% and D150 brand – 1% or about 8 thousand m^3 of mineral thermal insulation. Fig. 4 shows the dynamics of AAC production by density.

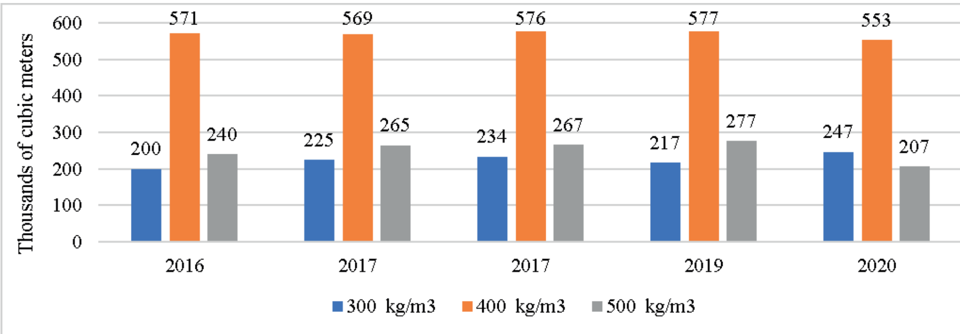

Fig. 4. Dynamics of aerated concrete production by density produced by "Aeroc". *Source*: own study

"Aeroc" initiated the amendments to the State Standard of Ukraine "Cellular concretes. General Specifications", according to which the insulating concrete can be now considered as aerated concrete with average density 100, 150, 200, 250, 300 and 350 kg/m^3. Aerated concrete density D300 and above with a compressive strength of 2.5 MPa is classified as structural and insulating aerated concrete, which corresponds to the regulatory requirements of the European standard EN 771-4.

It should be expected that due to environmental reasons and combustibility, the use of traditional thermal insulation (mineral wool, polystyrene foam) will be displaced by environmentally friendly mineral insulation – lightweight gas concrete, especially for the internal insulation of buildings.

Table 2 shows the comparative characteristics of low-density AAC produced by Ytong, Aeroc and Bonolit Group.

Table 2. Characteristics of low-density insulation aerated concrete

Material properties	Type of mineral aerated concrete insulation		
	Ytong Multipor	Aeroc Energy	Bonolit Group
Density, kg/m^3	D100 – D115	D150	D200
Thermal conductivity, W/m·K	0,045	0,05	0,055
Compressive strength, MPa	≥ 0,35	0,5	0,5
Fire resistance	Euroclass A1		
Vapor permeability, mg/(m * h* Pa)	0.3	0.3	0.3

The main properties of manufactured light insulating aerated concrete are very similar. While Ytong Multipor products are widely used on European markets, AAC produced by Aeroc and Bonolit Group is produced for domestic consumption. Aeroc is working out the technology of AAC production with the density of 125-130 kg/m^3. TheTurkish company EGE Gazbeton and some Russian manufacturers share information about the production of individual batches of insulating aerated concrete of D200 brand.

Table 3 shows the data on energy intensity of Aeroc AAC production with different densities and the dynamics of the relative consumption of the binders (cement and lime). Binder consumption of the heaviest aerated concrete brand D500 is taken as 100%.

Table 3. Consumption of raw materials and resources for AAC produced by Aeroc (Ukraine)

Rate	500 kg/m^3	400 kg/m^3	300 kg/m^3	150 kg/m^3
Cement and lime consumption, %	100	93	93	75
Electricity consumption during sand grinding, KW / m^3	8	6,8	5,6	9
Gas consumption, m^3/m^3	7,5	6,2	5,4	4,5

It can be clearly seen that as the density of AAC decreases, the relative consumption of binders decreases. Natural gas consumption in the production of aerated concrete decreases as its density decreases.

Fig. 6 shows the priority organizational and technological solutions at Aeroc for reducing the energy intensity of AAC production.

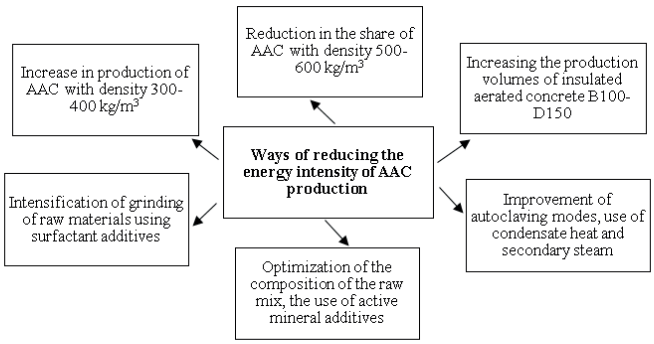

Fig. 6. Organizational and technological solutions aimed at reducing energy consumption of AAC production. *Source*: own study

5. Conclusions

According to the IEA, up to 40% of all energy in the world is used to maintain buildings. The main source of greenhouse gas emissions is the combustion of hydrocarbons, which has reached critical levels.

The share of construction of individual low-rise buildings (up to 3 floors) is increasing in many countries. As a result, construction of low-rise buildings requires more walling materials.

AAC is one of the most popular wall materials in Ukraine and other countries. Its advantages are low energy consumption as compared to traditional wall materials and higher thermal insulation properties. The share of AAC in the structure of wall materials of European countries is 20-30%, in post-soviet countries it reaches up to 40-60%.

The problems of energy saving remain a matter of pressing concern. That is why reducing greenhouse gas emissions in production of walling materials should be considered as a priority. It can be achieved by using active mineral additives, as well as by switching to production of low density blocks (300-400 kg/m^3).

The energy-ecological policy of Aeroc (Ukraine) is aimed at sustainable development by improving the structural quality of AAC, increasing the share of structural-insulating D300-D400 brand AAC and increasing production of environmentally friendly mineral heat insulation with a density below 150 kg/m^3.

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SIMURG: A new model for the integrated assessment of sustainability

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Abstract: Sustainability assessment is one of the basic issues in the agenda of public authorities and it requires practical tools to measure performance in terms of sustainable development goals. Most studies in literature deal with only one dimension of the problem of environmental components of sustainability. These studies discuss entities at only one level (cities, buildings, etc.), and one layer (green, smart, etc.) in selected dimensions. The literature includes no models that claim to provide an integrated assessment of entities' performance in the 3D Cartesian system. The presently available models do not offer solutions that would be applicable in practice. SIMURG (A performance-based and **S**ustainability-Oriented **I**ntegration **M**odel **U**sing **R**elational database architecture to increase **G**lobal competitiveness of construction industry) proposes using layers and their KPI sets in the assessment process. In addition to philosophical, organisational, integrational, and computational models, this study aims to develop a lean architecture of a relational database model by eliminating ineffective solutions in the practical dimension, i.e. in the computer model. The model can be used by individuals to help them choose built environment whose characteristics match their expectations. Public authorities can utilise the model to increase the level of accountability, transparency, and legitimacy in their decision-making processes.

Keywords: Sustainability Assessment; 3D Cartesian System, Philosophical Model; Frame Model; Organisational Model; Integrational Model; Computational Model; Computer Model

1. Introduction

There are certain difficulties and limitations involved with traditional planning, design, and production processes of the built environment, such as conflict of interests of shareholders, incomplete documentation, lack of coordination among the organisations at different phases of the production process, lack of control in the construction phase, etc. For this reason, there may be issues related to the results of this processes. While the clients/entrepreneurs are taking all the critical decisions to increase their profits, the end-users, especially in developing countries, feel aggrieved for various reasons such as inadequate codes and regulations, lack of information about standard performances that must be provided by products, defective mechanisms that are supposed to protect the society. Moreover, economic losses on a national and global scales occur, limited resources are wasted, and difficulties related to sustainable development process increase. Therefore, this process must be re-thought and replaced by alternative approaches, particularly with the support of computer-based tools, in order to increase transparency and accountability of decision-making processes, primarily in developing countries.

There are numerous studies in the "sustainability" area which are concerned with the "analysis" part of assessment-related problems regarding the built environment, but only few remarkable studies tackle the "synthesis" of computational and computer models that are based on a conceptual model with a holistic view. There is a limited number of studies which take a holistic perspective on the nature and components of the problem and attempt to propose an integrated solution that would have interrelated components in both the conceptual and the practical dimension. A comprehensive "systems approach" is essential for effective decision-making regarding global sustainability since industrial, social, and ecological systems are closely linked [1].

Most studies in the literature address only one single dimension of the 3D Cartesian system of sustainability, i.e., the environmental, economic, or social dimension. An exhaustive table which presents the results of a meta-analysis of the studies on the subject can be found in Ulker et al. [2]. Even more examples of papers in this area can be mentioned if we take into consideration those concerning all three environmental dimensions of sustainability in the 3D Cartesian system, and dozens of entities/facts within these dimensions. Yet, it is obvious that these studies are focused on a single or limited number of entities/facts, although defining a comprehensive framework model must be the first step before focusing on specific parts of the whole system.

As for the computation models presented in the related studies in the literature, all models have their computation processes limited by the part of the built environment they are focused on. These models are not comprehensive because in their computations, they fail to consider the interrelationships among the dimensions of the 3D Cartesian system in their integrated assessment of sustainability. Some of the framework models that attempt to solve the problem using such approaches as Life Cycle Assessment (LCA), Life Cycle Inventory Analysis (LCI), and Life Cycle Cost (LCC) are not suitable for the assessment of the social dimension of sustainability. As for the computation process, various studies suggest using a number of methods, such as Multi-Attribute Utility Analysis [3,4], Performance Benchmarking [5-7], Technique for Order Preference by Similarity to Ideal Solution/TOPSIS [8,9], Multi-Criteria Decision Making [10], Machine Learning [11].

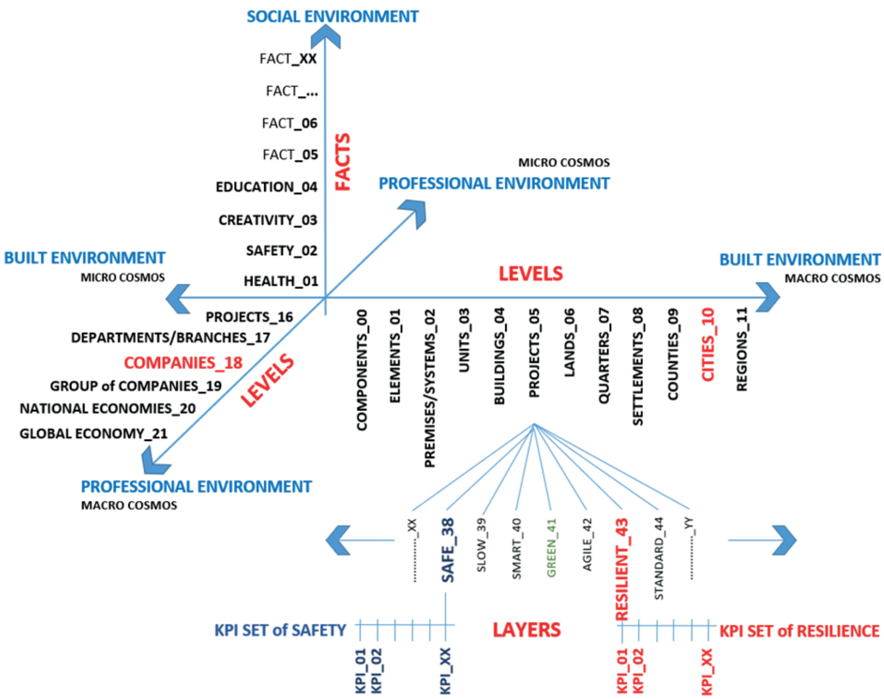


Fig. 1. Generic example of the multi-dimensional, multi-level, multi-layer, and performance-based assessment model of sustainability proposed by the study. *Source: own study*

Examples of related studies in the literature include but are not limited to *a*. built environment dimension [12], *b*. economic environment dimension [13,14], *c*. social environment dimension [15-19]. Similarly, these studies are concerned with only one level in selected dimension such as *a*. product dimension_cities level [16,20,21], *b*. product dimension_buildings level [15,22], *c*. process dimension_companies level [13,14], *d*. process dimension_projects level [23]. Some studies focus on only one layer/label/concept for the assessment of selected entities such as *a*. green [15,24], *b*. smart [16,17,20,21], *c*. resilient [1,25].

None of the above-mentioned studies present a comprehensive approach and thus they do not address organisational or integrational issues in their conceptual models. There are more examples of related studies concerning all environmental dimensions of sustainability in the 3D Cartesian system if we take into consideration those that look at dozens of entities/facts within these dimensions. However, they are focused on a single or limited number of entities/facts and do not discuss the conceptual part of the model or organisational/process-related and integrational sub-models that must be included in it.

2. Research problem statement

As for the studies that adopt a holistic framework and provide comprehensive computational and computer models for the solution of the assessment problem of built environment regarding the sustainability concept, there are few examples in the literature. None of these studies consider the mutual relationships between entities in the dimensions of sustainability in their computational models. Moreover, none of these studies include a practical model that would be the proof of the holistic and comprehensive approach adopted in the conceptual model and show how realistic the proposed model is and what the sources of information are, etc.

Gathering required information is a real problem, since information systems used for this purpose have no standardised structure. Moreover, this information must be organised in a distributed system, and there is no authority that would handle and coordinate these processes. Citizen-based subjective information related to weights and scores for the assessment can be provided by the end-users of the model. Yet, for the objective part of the assessments, official databases of governmental institutions must be reengineered to ensure their interoperability in providing the required information related to entities in the assessment process. Most models in the literature do not address the interoperability issues that explain what the information sources are and how they can be integrated for the assessment of the sustainability of built environment. Therefore, these studies do not provide satisfactory information about the architecture of the models proposed.

Ahmad and Thaheem [26] described a simplified computation model of sustainability in social/economical/ environmental dimensions, which is based on life cycle cost (LCC) and life cycle inventory analysis (LCIA); they used two hypothetical preliminary projects for comparative assessment. Their model places emphasis on "*integration*" based on building information modelling (BIM). In their complementary paper, the authors [27] lay emphasis on BIM and present a comparative analysis of various designs using real estate plugin at the "*cities*" level. Moreover, in their third paper, they propose a conceptual model [28] which aims to make only an economical assessment of the built environment. The last paper of the authors [29] proposes an assessment framework for a "*residential building*" related to social sustainability, by considering the implications of the frame model on BIM. They stress that though their fourth paper intends to emphasise "*social*" sustainability, the overall study addresses all sustainability dimensions [30].

Garau and Pavan [31] and many others use the layer/label/concept "*smart*" in the assessment of built environment entities at "*cities level*" and under the proposed evaluation framework, the quality of life in a given city is evaluated. The authors indicate that a smart city evaluation framework should encompass different "*sectors*", rather than focus on a single one. This study is one of the rare examples that mention the integration of two dimensions of the 3D Cartesian system of sustainability, i.e. the built environment and the economic environment dimensions. Another study conducted by Leach et al. [32] presents a conceptual framework that incorporates an '*intelligent reductionist'* approach to urban policymaking. It comprises four tiers, i.e., lenses, goals, actions, and indicators, derived from the classic strategic planning hierarchy; this framework ensures a holistic approach. The least granular of these four tiers is 'lens'; there are four lenses, aligned to the four commonly accepted pillars of sustainability: society, environment, economy, and governance.

Elyamany et al. [13] approach this problem at three different levels; *a*. construction industry; *b*. company; and *c*. project; and they propose an integrated mathematical model for the calculation of performance of construction companies regarding these levels. All studies that focus only on specific entities and/or attempt to define/design a framework model certainly contribute to the area and are valuable; however, we need a more comprehensive and holistic approach and a model which would cover almost all aspects of the conceptual dimension and the corresponding components in the practical dimension. Such a model must include proposals for the basic components stated below.

3. The aim and objectives of the study

As a result of the assessments made, it was concluded that the model which would be developed as a solution to the identified problem must include and introduce the components/sub-models of the solution in the following dimensions (Figure 2):

A. The Conceptual Dimension

- Philosophical/Paradigmatic Model,
- Framework Model,
- Organisational/Process-Related Model,
- Integrational/Interoperability Model,
- Computational/Assessment Model,

B. The Practical Dimension

- Computer/Software Model,
- Implementation Model.

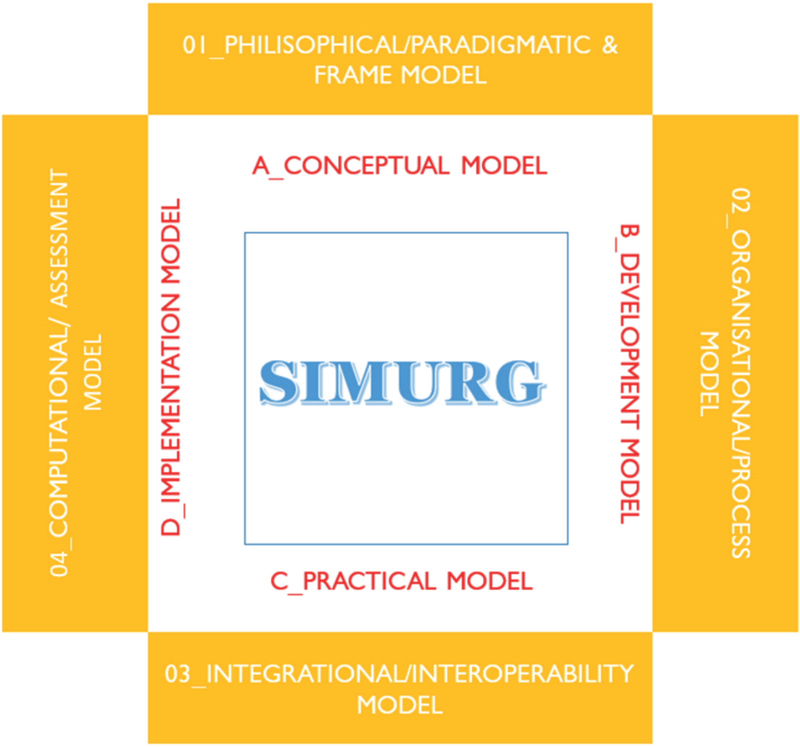


Fig. 2. The components of the conceptual model as the objectives of the SIMURG research. *Source: own study*

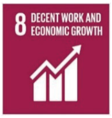
SIMURG (A performance-based and **S**ustainability-Oriented **I**ntegration **M**odel **U**sing **R**elational database architecture to increase **G**lobal competitiveness of construction industry) is our response to the problem stated above. The name of the model is the title of a Persian tale, which has corresponding versions in Turkish and Western cultures as well. It tells of 30 birds searching for their leader called SIMURG. At the end of their journey, they eventually discover that there is no such bird named SIMURG; however, they are all SIMURG as a whole. The indirect reference to the concept of "governance" in this tale, in the context of built environment, provided one of the basic inspirations for this study. The entities at all scales and levels of the built environment need to use the language of human-centric approaches by placing the governance and sustainability concepts in the centre of all problems and solutions. This paper tries to explain the structure and interrelationships of the models mentioned above.

4. Methodology of the study

Model development studies mostly require iterative processes. Comprehensive models increase the complexity of these processes.

Table 1. Completed sub-Projects of SIMURG and their related Sustainable Development Goals (SDGs)

RELATED SDG	NAME of THE MODEL	DIMENSION	LEVEL	LAYER	DETAILED INFORMATION about THE MODEL
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	SIMURG_ IDEPRO	ECON_ENV	SECTORS	STANDARD	A Model for the Integration of Design and Procurement Processes in Construction Projects: PhD dissertation by Arslan and Kanoglu [33,34].
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	SIMURG_ MORPHO_ BLUE	BUILT_ENV	PREMISES	STANDARD	A Performance-Based Integrated Model at the Building Premises Level for Kitchen Design: R&D project by Yazicioglu and Kanoglu [35-40] for Kelebek-Dogtaş Furniture Systems.
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	SIMURG_ COMMON_ _BLUE	BUILT_ENV	PREMISES	STANDARD	A Performance-Based Integrated Model at the Building Premises Level for Bathroom Design: Unpublished MSc thesis by Konuk [41].
11 SUSTAINABLE CITIES AND COMMUNITIES	SIMURG_ CITIES_	BUILT_ENVR	CITIES	CREATIVE	A Performance-Based Integrated Model for Design and Evaluation of Sustainable and Sophisticated Solutions at the City Level for Creativity Layer: PhD dissertation in progress by Varlier, Ozcevik and Kanoglu [42].
11 SUSTAINABLE CITIES AND COMMUNITIES	SIMURG_ CITIES_	BUIILT_ENV	CITIES	MULTI L LYR	A Performance-Based Integrated Model for Design and Evaluation of Sustainable and Sophisticated Solutions at the City Level for Multi-Layer Benchmarking of Cities: PhD dissertation in progress by Ulker, Kanoglu and Ozcevik [43].
8 DECENT WORK AND ECONOMIC GROWTH	SIMURG_ HELMET	ECON_ENVR	COMPANIES	STANDARD	An Integrated Solution for the Departments of Health of Laborers and Safety of Work in Construction and a Model for the Evaluation and Tracking the Performance of Department, MSc thesis by Erdogan [44].

	SIMURG_ ARCADIA	ECONO_ENV	COMPANIES	STANDARD	A Performance-Based Integrated Relational Database Model for the Assessment Processes of Architectural Design Competitions in Professional Practice and Architectural Design Studios In Academia, MSc thesis by Akturk [45].
	SIMURG_ CONCRETE	BUILT_ENV	COMPONENTS	STANDARD	A Performance-Based Integrated Model for Design and Evaluation of Sustainable and Sophisticated Solutions at Building Components Level: Unpublished MSc thesis by Serifoglu [46].
	SIMURG_ PERISCOPE	ECONO_ENV	DEPARTMNTS	STANDARD	A Performance-based Integrated System for Construction Companies' Procurement Departments Based on the Variations of Estimated and Actual Risks: PhD dissertation by Altindag [47].

Before attempting to develop a framework model, it is necessary to gain a good understanding of the relationships among the components as well as the relationships between each component and the whole system. Thus, in accordance with the draft version of the framework model proposed, components of the system were studied in various research projects, master theses, and PhD dissertations written by the authors (Table 1).

During these studies, lessons learnt from the processes of developing sub-models that are meant to operate within the main system were used for the design of the core part of the model that integrates the components. In this way, a bottom-up approach in an iterative process was adopted and practiced in the development/investigation processes of the relationships between the components and the core part of the model. A comprehensive "systems approach" is essential for effective decision-making regarding global sustainability, since industrial, social, and ecological systems are linked [1].

5. Synthesis of the proposed model

5.1. The philosophical/paradigmatic model

Sustainability is not a concept that is taken into consideration by the corrupted political system, entrepreneurs, or financial institutions, who tend to abuse it, since the built environment is one of the most profitable investment areas in most places of the world. However, the main concept among those that can be achieved by the integrated use of all key concepts for the well-being of society is sustainability. It can be achieved only by matching the basic requirements of life – not only of human beings, but also all living creatures – with their expectations and attributes in an appropriate and balanced way. In our society today, requirements/expectations/identities of citizens fail to be match up with the attributes of built/professional/social environments; i.e. parents persuade their children to enter professions that are supposed to provide high income during their professional lives; individuals invest their financial resources in houses that are only supposed to be highly profitable investments; municipalities support the investments of built environment entities that do not match up with the identities/souls of the cities, etc., and the reason for that is the ill-defined value system imposed on the individuals of the society, especially during the last four decades in Turkey.

5.2. The frame model

A comprehensive and holistic framework model is indispensable to be able to increase the accuracy of the assessment process of the performance of entities not only in the built environment dimension but also in the other two dimensions of the 3D Cartesian system in SIMURG. In order to achieve this goal, researchers have to tackle a trade-off problem between the level of complexity and versatility of the model proposed, and the present study aims to develop a model that can measure/assess/explain the performance of the environmental dimensions of sustainability more accurately and successfully compared with the other models reported in the literature and professional practice. In other words, the comprehensive/complicated character of these models does not guarantee the success of the solution and the “less is more” statement that was one of the popular mottos of the architectural practice in the 1960s must also be considered in the design of the proposed framework model. The current study aims to propose a holistic model that uses “the system approach” to define the relationships between related entities and to design *a*. multi-dimensional, *b*. multi-level, *c*. multi-layer/label architecture to express these relationships among the dimensions of the Cartesian system of sustainability and among the entities on various levels of these dimensions. This approach makes it necessary to analyse the basic components of the system in four main sections: *a*. environmental dimensions of sustainability, *b*. entities on each level of these dimensions, *c*. layers/labels/concepts of assessment of sustainability, *d*. methods/tools of assessment of sustainability. These classifications clarify our perception of the above-stated problem and thus the conceptual model can be interpreted more accurately.

All entities which are located in the 3D Cartesian system of environmental components of sustainability can be assessed by using performance-based assessment approach that applies various sets of Key Performance Indicators (KPIs). These sets are expressed by some well-known terms such as smart, slow, safe, green, resilient, etc., and are referred to as “layers/labels/concepts” in this study. In this context, assessment can be made for a given group of cities by using, for example, the “smart city” KPI set or “safe city” KPI set. The resulting performance values of these both entities at the “*cities level*” will be different at the end of the comparative assessment process depending on the KPI set used. Just like in the case of entities in Product-Related/Physical/Built Environment dimension, i.e., cities in this example, it is possible to make an assessment of entities at, for example the “departments”, “companies” or “sectors” levels in the Process-Related/Professional/Economic Environment dimension, and so on. In this way, all companies from the “contractors”, “designers”, “manufacturers”, or “suppliers” categories can be assessed, ranked, and compared internally; just like all industrial segments (sectors) within national economies or all national economies within global economy.

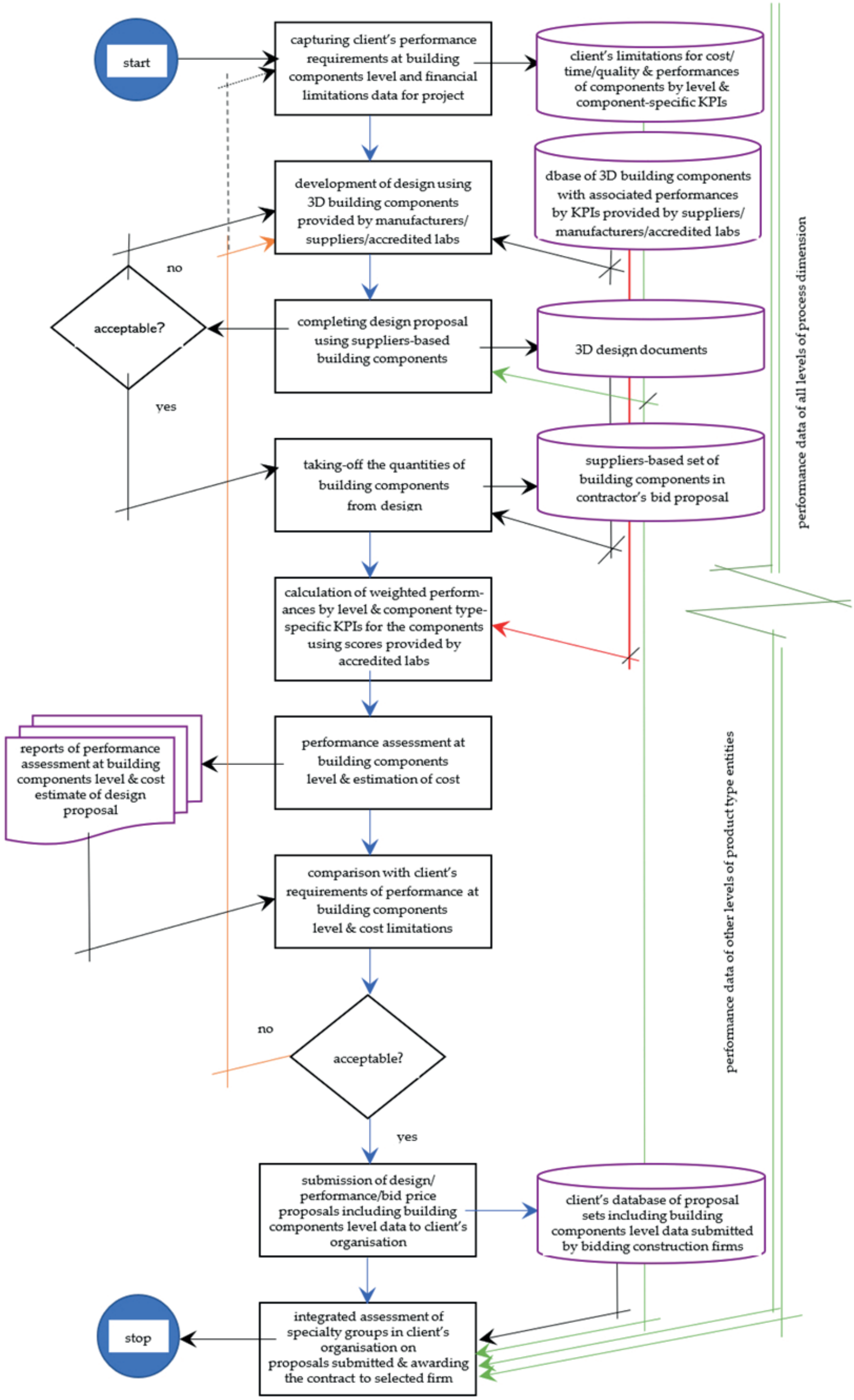


Fig. 3. Sample flowchart of the performance-based assessment for component level objects. *Source: own study*

5.3. The organisational/process model

The performance-based assessment approach suggested in the SIMURG (*A performance-based and **S**ustainability-oriented **I**ntegration **M**odel **U**sing **R**elational database architecture to increase **G**lobal competitiveness of construction industry)* project entails using the services of accredited institutions/laboratories which issue product/process-related certificates for certification-based assessment of entities at all levels of product-related (physical/built), process-related (professional/economic) and human-related (cultural/social) environments. This approach calls for re-thinking the entire production process of the built environment and proposes that a new organisational and process-related model must be developed from scratch. The entities at “01_components of elements” and “02_composite elements” levels must be tested, scored, and certified by accredited labs; the certificates must include the performance values of standardised KPIs of components/elements. The entities at “03_premises of building units” and “04_buildings” levels must be tested by simulation software for the assessment of the acoustical, fire-resistance, earthquake/wind effects, etc., and then scored and certified by design consultancy offices or accredited/authorised governmental or independent institutions, and so on.

These certificates and KPI-based performance values must be attached to 3D models of building components/elements/premises, etc. All design documents must be supported by these certificates and various kinds of evidence, such as physical test results of components/elements or virtual simulation files of acoustical/structural/fire/etc. systems, through the entire approval process performed by governmental offices. This information including 3D objects associated with KPI-based performance values can be qualified as BIM_6D objects.

Flowcharts of performance-based assessment of entities and processes of delivery/production of these entities at various levels of the 3D Cartesian system were developed first for each entity in the dimensions of the 3D Cartesian system. As an example, Figure 3 presents one of these processes related to “01_building components level” entities in the built environment dimension.

Manufacturers of building components/elements/systems must provide BIM_6D models of their products on hosting websites by publishing certificates which include performance values of standard KPIs, so that designers can make a performance-based assessment of their design even at the preliminary design phase by using these components included in their design documents. Thus, it will be possible to receive the performance assessment reports from the model instantly, just like take-off lists or bill of quantity reports. It is possible to locate big data systems with distributed architecture in one single place on the Internet in order to make building components/elements available for designers. Moreover, private/public sector service providers who would retrieve this information from various websites and offer a combined database to the design/construction professionals are likely to appear on the market soon.

5.4. The integrational/interoperability model

5.4.1. Interoperability at the Conceptual Level: The Information Classification Systems

Building Information Modelling (BIM) is one of the significant issues for any model that is designed as a solution to the stated problem. It is one of the primary tools even for modelling historical buildings [48,49]. The performance-based approach will be in the 6D_Sustainability dimension of BIM after the 4D_Time, 5D_Cost dimensions. Interoperability of the product and process-related entities throughout the building production process can be achieved thanks to information classification systems such as OmniClass, MasterFormat, UniFormat, etc.

5.4.2. Interoperability of the Computational Model: The Solar System Simulation

The *Solar System Simulation*, inspired by the interrelationships within our solar system, is essential for the integration/interoperability model and calculation/assessment models of SIMURG. It is presented in Figure 4. It shows the expansion levels of built environment entities in the product-related/physical/built environment dimension; the expansion levels of process-related/professional/economic environment in the process dimension, and a set of social facts in the human-related/cultural/social dimension of the 3D Cartesian system.

All entities at certain levels of environmental dimensions of sustainability in the 3D Cartesian system have their "spherical sizes" that represent the impact factor or "weight" of the entity to be assessed. In other words, the spherical sizes represent the "*mass*", i.e. "*weight"* of the entity to be used in the performance-based assessment of sustainability. As for the "*distance*", it represents the "*scores*" of the factors (KPIs) given by experts or users. The "*force of gravity*" equation provided inspiration for the research team to propose an integrated calculation model. It was modified and converted into SIMURG's computational/assessment model, which takes into consideration mutual interactions among the dimensions of the 3D Cartesian system in the assessment process.

The entity selected for assessment, for instance, can be a specific manufacturer/supplier/designer/contractor company at "02_companies" level if government departments require the calculation of companies' performance in the national construction industry when assessing their eligibility for financial support; or it can be an entity from the "03_departments/branches/dealers" level if construction companies need such calculations for monitoring the performance of their departments and developing corrective policies for these departments which are consistent with companies' strategic priorities.

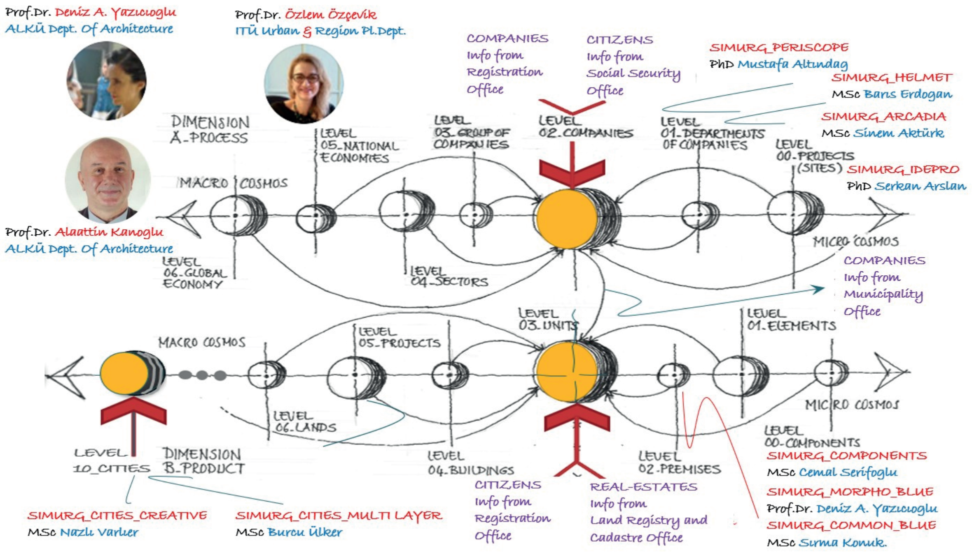


Fig. 4. Solar System Simulation, which is the backbone of SIMURG's integration and calculation models and of the current subprojects matching with various levels of entities of the built environment. *Source: own study*

The master project was designed to include research on and development of related sample models at all hierarchical levels of the performance-based assessment in the above-stated dimensions of the 3D Cartesian system.

As a rule, entities in the product-related/physical-built environment dimension are the essential subjects of assessment. In other words, assessments of entities/facts in other dimensions, i.e., in both the economic and the social dimension, are used to enable a holistic and more accurate assessment considering the effects of these dimensions on the performance of built environment entities. Still, they might be used to make assessments separately within the boundaries of their contexts if, for example, it is a government requirement to compare the performances of groups of companies in construction/textile/mining/etc. industries separately. After determining the entity of the built environment to be assessed, the subsequent step is to select the concept/layer/label for further analysis. The chosen concept, such as green, smart, slow, safe, etc. should be one that matches with the expectations of individuals or institutions in terms of the identity/character of the entity. Each concept/layer has its own set of KPIs including associated impact factors/weights. The scores are supplied by experts and individuals/institutions separately so that both objective and subjective assessments can be included and value systems of individuals in the society can be investigated.

Since the relationship between citizens and the built environment is established at the “03_building units” level by the occupation information recorded in a public database maintained by the government, all the secondary level information such as educational, social, cultural, health-related, crime-related, etc. data related to the citizens recorded by other government offices can be accessed and linked/combined at the desired levels of built environment entities in the model. For example, the arrows in Figure 4, show that entities at various hierarchical levels of the built environment dimension will influence the performance of the selected entity at “03_building units” (apartment/office, etc.). For that reason, the selected entity is located at the end of the arrow. If the entity to be assessed is, for example, at “10_cities” level, all the arrows would indicate this entity. Moreover, the changes in sizes of the spheres (scores) and distances of other entities (weights) to the selected entity require a new calculation process to be added to the computational part of the model.

5.4.3. Interoperability of the Practical Model: Communication with Governmental Databases

The data required by the model can be retrieved by various methods and tools from e.g. governmental databases, surveys, etc. Until now, researchers have used two basic approaches to examine the quality of urban life: the “objective” approach, which is typically confined to analysing and reporting secondary data – usually aggregate data that are mainly available from official government data collections, including the census, at different geographic or spatial scales – and the “subjective” approach, which uses social survey methods to collect primary data at the disaggregate or individual level, and focuses on peoples’ behaviours and assessments, or their qualitative evaluations of different aspects of urban life [31]. Selecting or designing a performance assessment framework and indicators useful for policymaking requires careful consideration; any given framework should be holistic with minimal overlap, be simple, include subjective and objective perspectives as well as quantitative and qualitative data, be usefully organised, and be relevant to decision-making [32].

SIMURG suggests using governmental databases in the “objective” approach; it does not require any other information sources such as surveys since the required “subjective” and individual data will be provided by citizens, who are supposed to subscribe to the service to be able to use the model via their password-protected pre-defined account on the platform. Thus, personal/subjective data will be provided directly by citizens in addition to officially verified individual data organised in the databases of the relevant government departments. Governmental databases are supposed to organise real-time data about all entities and facts related to physical, economic, and social dimensions. Of course, the governments cannot/must not share personal details included in these databases; however, the maps or generalised reports based on the information recorded in these databases should be accessible to citizens/associations/entrepreneurs/institutions, and the entire society to be used in their decision-making processes. Providing equal opportunities to individuals in the society and institutions/companies in the economic segments of the country regarding the accessibility of information is the essential factor of sustainability.

Citizens’ residence information is the key factor in the model for combining information from various databases of a distributed network. Built environment entities at “03_units of buildings” level (and also “06_lands” level) are recorded in the Cadastral Information System (TAKBIS: Tapu Kadastro Bilgi Sistemi) database of Cadastral Offices of Turkish governmental departments with their unique real estate IDs, and the associated residential information with the unique Social Security Numbers or IDs of citizens. The quality information about concrete in structural systems of buildings is handled in Electronical Concrete Tracking System (EBIS: Elektronik Beton İzleme Sistemi) database and organised by the related department of the Ministry of Environment and Urbanism, and so on.

On the other hand, while residence information concerning Turkish citizens is recorded in the Civil Registry System (MERNIS: Merkezi Nüfus İdare Sistemi) and the Address-Based Registry System (ADNKS: Adrese Dayalı Nüfus Kayıt Sistemi) databases run by the Office of Civil Register, other records related to various social facts and activities the citizens are involved in are recorded by various governmental units or authorities; e.g. crime information is organised in the National Network of Justice System (UYAP: Ulusal Yargı Portalı) database of the relevant offices Ministry of Justice; information on diseases and treatments of citizens is organised in the Health Information System (E-NABIZ: Elektronik Sağlık Enformasyon Sistemi) database of the relevant offices of Ministry of Health, and so on.

Information related to social/cultural/economic/etc. activities of citizens organised in various databases located in a distributed architecture network can be matched up with built environment entities and by using occupation information about citizens at “03_units of buildings” level of the Solar System Simulation via the unique IDs of citizens. As a result, various “maps” of social facts and activities based on officially verified real-time/accurate data related to various levels of the built environment such as buildings, projects (gated communities), quarters, settlements, counties, and cities can easily be produced. Using these maps may increase the level of precision and accuracy of planning studies and assignment of the required resources; i.e., the right number of medical experts will be assigned to public hospitals by governments, or private hospitals may predict demand for medical supplies, or simply capacities of educational institutions can be identified, etc.

The interoperability of the model provides a challenge that is not related to the ordinary database functions of *combining, grouping, sorting, filtering*, and *customising* data recorded in various databases of governmental offices. The challenge is related to what is not seen at first sight and what is hidden behind the visible relationships. The correlations among various entities, the relationships between dependent and independent variables can be instantly revealed without using statistical analysis software or waiting for experts' analyses; pure logic and professional background of architecture/construction experts are enough to make meaningful assessments by using this powerful tool. Governments are not supposed to share the citizens' details which are recorded in three-tiered architecture databases of governmental offices; however, final reports can be made accessible for all as suggested above.

5.5. The computational/assessment model

"Performance" is a measurable phenomenon. The level of performance is as important as attaining production goals. "What method of measuring performance is used" and "how performance can be increased" have been some of the main topics discussed in recent years by the shareholders of the construction industry, academia, and literature on the construction industry in addition to many other sectors. There are numerous studies and publications in the literature which describe models developed to measure performance at various levels of the environmental dimensions of the 3D Cartesian system of sustainability. Yet, none of these studies and models have proposed an integrated approach to the assessment of sustainability for the various hierarchical levels of built environment dimension by using various sets of KPIs of the layers/labels/concepts selected for assessment. The performance-based assessment approach seems to be the only conceptual tool that provides a common calculation and assessment method that must be placed at the core of computational and integration models. Yet, it requires well-organised management of distributed information systems managed by public and private sector institutions with a novel organisational pattern in addition to a set of equations that is needed for calculating the performance values of the compared entities using their arithmetical scores of sustainability. Examples of calculation models in the literature are limited to entities at certain levels of the built environment, such as building components, buildings, or cities.

The model calculates the total performance of a desired built environment entity using the equations presented below. The entities to be assessed comparatively can be, for instance, a set of building units at the "03_building units" level which are located at various locations/addresses in different cities. Calculations required for the assessment of performances of these building units will be the weighted sum of performance values of each level of the built/physical environment (BE) dimension; yet, this is not enough. Moreover, performance values of the manufacturer/designer/ supplier/constructor/etc. companies which were involved in the production process of these building units must be retrieved from the professional/economic environment (PE) dimension. Finally, the third performance value of social facts in the third dimension of the 3D Cartesian system, that is cultural/social environment (SE) dimension, in total with its associated weight is required for the calculation of the total performance of selected building units. The equations of these weighted performance values of the three environmental dimensions of sustainability are presented below (Equations 1, 2, 3, and 4).

Score of Built Environ. (BE)= Dimension	$\sum_{i=1}^{l} \text{W\_BE}_i \; x \sum_{i=1}^{k} (\text{W\_KPI}_i \;\; x \;\; \text{S\_KPI}_i)$ (1)
l=	Number of hierarchical levels in the built environment (BE) dimension
W_BE*i*=	Weight of the entity at the level numbered (i*)*
W_KPI*i*=	Weight of KPI numbered (i) in selected layer given by an expert or user
S_KPI*i*	The score of KPI numbered (i) in the selected layer given by an expert or user
k=	Number of KPIs in the layer selected for assessment
Score of Profess. Envir. (PE)= Dimension	$\sum_{i=1}^{n} \text{W\_PE}_i \; x \sum_{i=1}^{k} (\text{W\_KPI}_i \;\; x \;\; \text{S\_KPI}_i)$ (2)
n=	Number of entities at level (*l*) in (PE) dimension that are involved in the production of (BE) entity
W_PE*i*=	Weight of the entity numbered (i) involved in the production of (BE) entity
W_KPI*i*=	Weight of KPI numbered (i) in selected the layer given by an expert or user
S_KPI*i*	Score of KPI numbered (i) in the selected layer given by an expert or user
l=	Level of selected entities of the professional environment (PE) dimension to be used in the assessment
Score of Social Environ. (SE)= Dimension	$\sum_{i=1}^{f} \text{W\_SE}_i \; x \sum_{i=1}^{k} (\text{W\_KPI}_i \;\; x \;\; \text{S\_KPI}_i)$ (3)
f=	Number of facts in the social environment (SE) dimension to be used in the assessment of (BE) entity
W_SE*i*	Weight of social fact numbered (i) in the (SE) dimension
W_KPI*i*=	Weight of KPI numbered (i) in the selected layer given by an expert or user
S_KPI*i*	Score of KPI numbered (i) in the selected layer given by an expert or user
k=	Number of KPIs in the layer selected for assessment
Total Score of Built Environ. (BE)= Entity to be Assessed	$\sum_{i=1}^{d} \text{W\_DIM}_i \; \text{x EQ\_DIM}_i$ (4)
d=	Number of dimensions (i.e., BE, PE, SE, etc.) to be used in assessment
EQ_DIM*i*=	Equation related to dimension numbered (i)
W_DIM*i*=	Weight of dimension numbered (i)

In Equation 1, the performances of each level of the built environment are calculated by using a selected KPI set (layer) as well as KPI-specific/level-specific associated weights and scores given by experts and users simultaneously, and thus the first component of calculation is achieved. As it can be seen in the illustration (Figure 4), there is an additional "inter-dimensional" relationship between "Level_02_Companies" in the Process Dimension and "Level_ 03_Building Units" in the Product Dimension, since the performance of entities at all levels of built environment cannot be calculated without considering the effect of performance of companies that takes place in the production process of these built environment entities. Another "inter-dimensional" relationship exists between the facts in the social dimension and built environment entities in the product dimension.

Equation 2 calculates the performance of each entity from the professional environment, for instance the manufacturer/supplier/designer/constructor/etc. companies which were involved in the production process which included the selected building unit. The equation uses a selected KPI set (layer) as well as KPI-specific/level-specific associated weights and scores given by experts and users simultaneously. Thus, the second component of the calculation is obtained. The performance of companies is calculated using performance values of departments/branches/dealers of these companies, such as safety, project procurement, human resources, etc. departments.

In Equation 3, performance of each fact of the social environment is calculated by using a selected KPI set (layer) as well as KPI-specific/fact-specific associated weights and scores given by experts and users simultaneously; and so the third component of the calculation is obtained. The model can be used by various shareholders of the built environment for numerous decision-making processes. For example, citizens may need assessments of building units to choose the most suitable ones to make a profitable investment or find the best one to live in. Similarly, policymakers in a municipality or ministry of construction and built environment may want to know the performance values of their settlements/counties/cities in terms of various KPI sets, such as green, slow, smart, safe, resilient, etc., to be able to determine the concept/layer that yields the highest score, which also means "the identity" of their settlement/county/city, no matter what the level of the built environment is.

Equation 4 represents the calculation of the final score of the entity as the sum of the weighted scores of environmental dimensions of sustainability on the 3D Cartesian system.

The weights of the impacts of entities/facts in all dimensions of sustainability are considered in these equations because of mutual relationships among these entities/facts that are modeled by the assumption referred to as *the Solar System Simulation* (Figure 6), which has already been explained above.

In its computational model, SIMURG proposes using a single layer/label/concept from the list of these layers, i.e. smart, green, safe, resilient, etc., and its KPI set in the calculations and assessment process of performance-based sustainability of any selected entity in the dimensions of the 3D Cartesian system of sustainability. In this approach, it is assumed that citizens select an appropriate label/layer/concept that matches their life paradigms, and they are able to prioritise related KPIs in the selected set by weighing them. This is why benchmarking entities in terms of their performance is based on a selected layer/label/concept.

5.6. The practical/computer/software model

5.6.1. The relational database architecture of the proposed software model

During the ongoing studies on SIMURG, the main result of the project, one of the basic problems to be solved has been the architecture of the relational database model. In the first attempts, built environment entities and certification systems which the performance calculations of entities at the hierarchical levels of the 3D Cartesian system are based on were defined in separate tables. It was found that matching certification data in one table type database object with related entities at various hierarchical levels of the built environment dimension that are defined in their separate hierarchical group tables in this fragmented structure is not a suitable solution regarding relational database logic.

In the second attempt, another architecture was suggested; certification data would be organised in separate table type objects in the database, in tables at two consecutive levels, i.e. information categories common to all entities in the main table and entity-specific particular information regarding relevant entities at various levels of the environmental dimension – in secondary level tables.

Figure 5 presents the lean architecture of the SIMURG relational database, which, however, does not include relationships with public databases of information on social issues such as health, education, crime, etc. yet.

Thus, after six consecutive attempts, we succeeded in overcoming difficulties in placing the related data in various tables of the database and managed to simplify the complicated structure of the relational database architecture of the model, arriving at the final lean solution given in Figure 6. This latest version of the model represents the final architecture including the relationships with public databases with information on social issues as well.

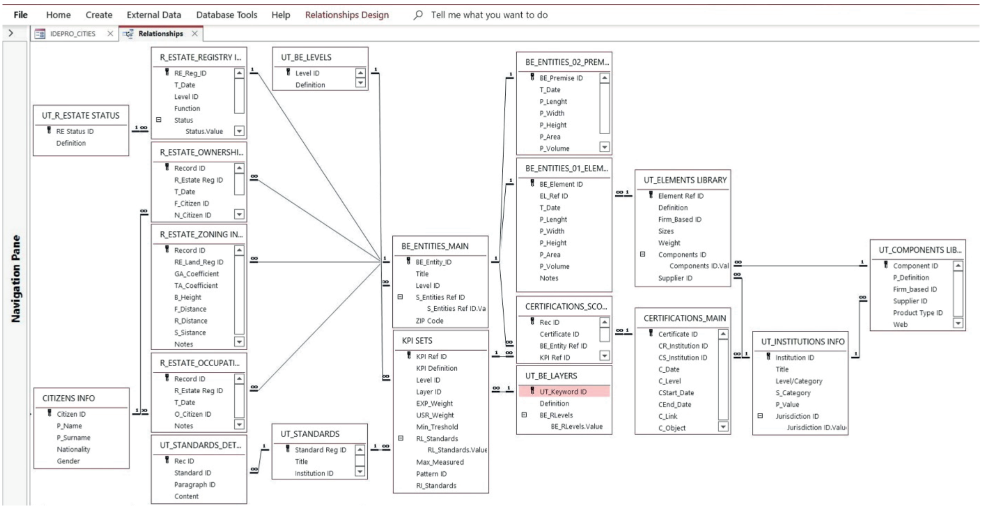


Fig. 5. The final and lean version of relational database architecture of the model without relations hips with public databases with information on social issues. *Source: own study*

5.6.2. The plug-ins of the proposed software model

Sub-projects of SIMURG listed in Table 1 adopt this frame and try to develop and propose an interoperable/functional model to work with it. The start-up screen of SIMURG is presented in Figure 7.

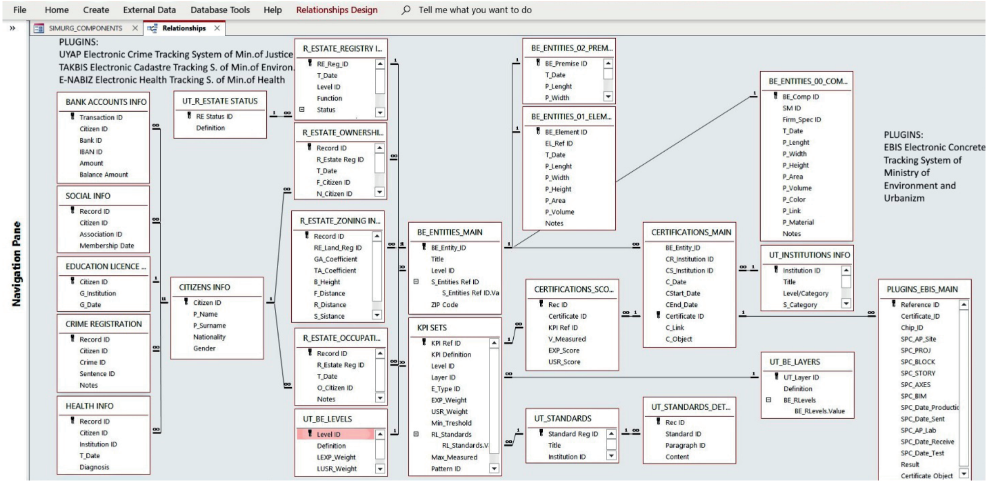


Fig. 6. Interoperability of governmental databases as plugins. *Source: own study*

Since citizens are connected to the built environment at "*03_Building Units Level*" via the MERNIS database maintained by the governmental unit of the Turkish Civil Registration and Citizenship Department of the Ministry of Internal Affairs, it is possible to obtain specific maps with information regarding crime (UYAP database of Turkish Ministry of Justice), health (E-NABIZ database of Turkish Ministry of Health), etc., at the selected level of built environment entities, such as projects, quarters, settlements, counties, or cities.

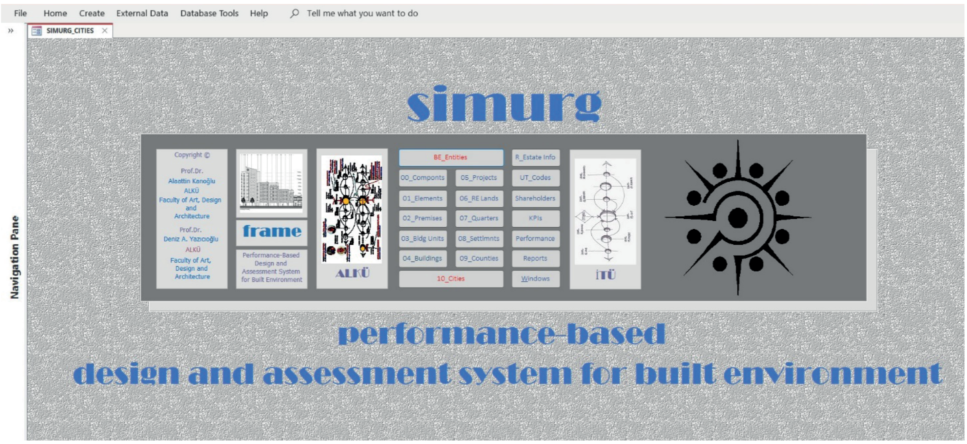


Fig. 7. The user interface of SIMURG software model. *Source: own study*

5.6.3. *The certification system of the proposed software model*

SIMURG proposes a certification-based assessment model. According to this approach, all entities at hierarchical levels of the 3D Cartesian system of sustainability are certified by accredited institutions/labs. The performance values of these entities can be calculated using the KPIs from the provided sets of layers/labels/concepts.

These values are included in the certificates issued by accredited institutions/labs for the analysed entities. In addition to these performance values given by expert institutions, the model requires taking into consideration subjective scores provided by citizens. This data is retrieved directly from citizens who want to use the system to make decisions based on their subjective value system. The session-based approach proposed by the model and the input provided by citizens subscribed to the platform make it possible to obtain a comprehensive set of data on both the objective and the subjective dimension and use it for the assessment of sustainability.

The entities and facts in the dimensions of sustainability can be imported from BIM-based design documents or can be defined manually in the database in a hierarchical structure. Performance-based calculations are made for each entity and fact in these dimensions using expert and user-based scores and weights provided by the certificates issued for company-specific components/elements/premises, etc. by accredited labs/institutions (Figure 8).

The model proposes a novel organisational approach to accreditation given by institutions/labs to entities at various hierarchical levels of the built environment and economic environment dimensions in the 3D Cartesian system. As far as the entities in the built environment dimension of the 3D Cartesian system are concerned, today in various countries certification of building components and elements is mostly limited by standards and norms such as DIN, BS, TSE, etc. In general, these are not performance-based certification systems. There are also other certification systems applied at buildings/projects levels, such as BREAM, LEED, etc. On the other hand, there are some certification processes applied globally in the assessment of professional entities in the economic dimension of the 3D Cartesian system, such as ISO 9000 quality management systems, which also do not provide performance-based certification. The literature that proposes certification of entities/facts at all levels of the built environment and economic/professional environment dimensions of the 3D Cartesian system and uses performance-based assessment does not offer an integrated and comprehensive approach. SIMURG proposes using different sets of KPIs for all entities in each dimension of the Cartesian system in addition to a certification system of these entities at all levels of these dimensions, without an exception. A comprehensive model, SIMURG_MORPHO_BLUE developed as one of the sub-projects of SIMURG by Yazicioglu and Kanoglu [35-40] for the assessment of the architectural design of kitchen premises, can be given as an example of “03_premises” level assessment model. It proposes a certification and accreditation system of premises-level entities in the built environment and also suggests how such a system should be organised.

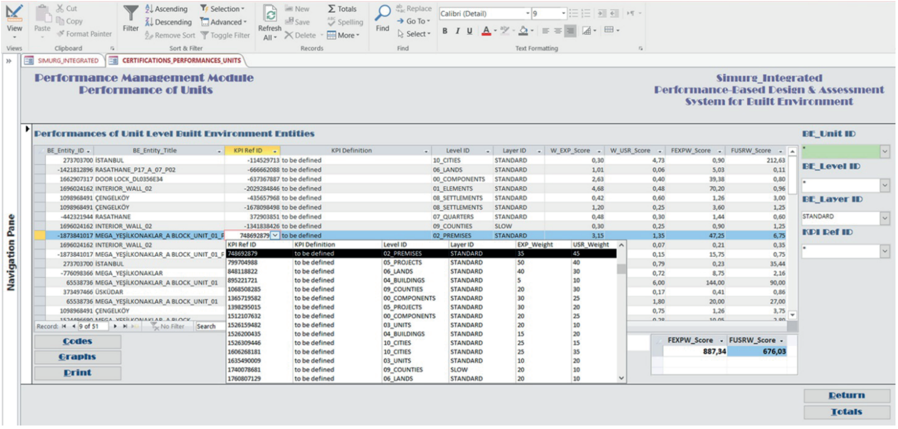


Fig. 8. Certificate-Based Performance Assessment by Expert (objective) and User (subjective) Value Systems. *Source: own study*

The relational database model developed on the MS Access platform proposes a certificate-based scoring approach. This approach currently exists at "00_building components" and "01_building elements" levels of the built environment and it is successfully being applied in some countries. In this approach, all the components and elements produced by manufacturers are registered, tested, and certificated by accredited institutions, such as national standardisation organisations. Some of the gated community projects apply for "green" certificates at "04_buildings" and "05_projects" levels; moreover, some cities have their green, slow, smart, etc. labels certified and declared by relevant authorities. Yet, these assessments are not made according to an integrated approach or model.

5.6.4. *The performance-based assessment system of the proposed software model*

SIMURG proposes an integrated assessment model that covers not only entire levels of the product-related/built environment (physical) dimension, but also the other two environmental dimensions of sustainability.

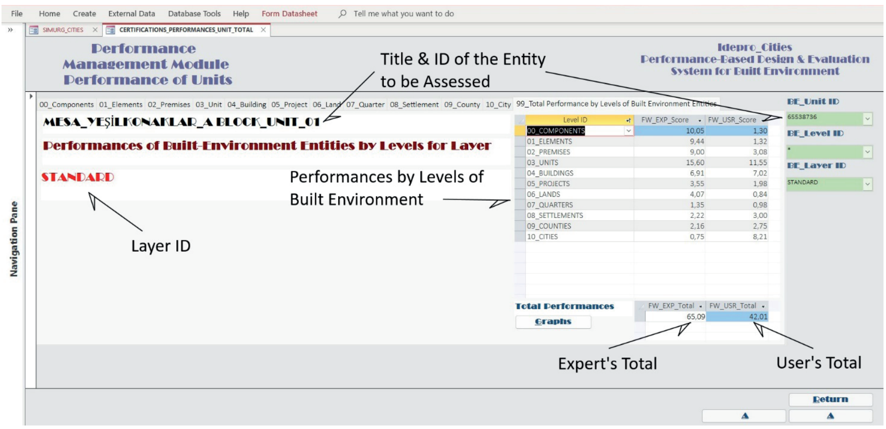


Fig. 9. Calculation of the performance of entities at various levels of the built environment and the total performance. *Source: own study*

As an example, final weighted scores of the entities of each level in the built environment dimension can be seen in Figure 9. These were calculated for a selected entity – an apartment unit, defined by a unique Unit ID of the building in the cadastral system.

Figure 10 represents these performance values in a graphical form. The effects of performance values of the entities in all dimensions are included in tabular and graphical (pie/histogram/radar/etc.) reports that use hypothetical data.

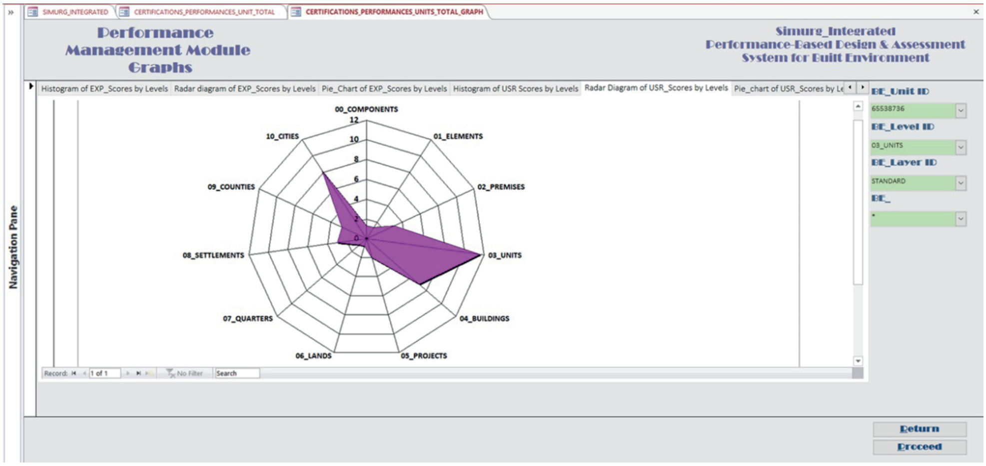


Fig. 10. Sample radar diagram of the components of the total performance of a selected building unit. *Source: own study*

6. Discussion

Sustainability is the key concept in integrating various aspects of life; for this reason, research teams from various disciplines examine this idea in their studies. It is not unusual for these disciplines to define the problem within the boundaries of their domains. Dividing the problem into its smaller components is also one of the basic rules of scientific research and this is why most studies related to the concept of sustainability have their limitations. However, the results of these fragmented studies do not offer a comprehensive perception of the big picture and convenient tools for policy makers to be able to increase the transparency and accountability of their decision-making processes. SIMURG, as the master project that encompasses dozens of potential sub-projects related to entities in all the dimensions of the 3D Cartesian system of sustainability, made it possible for multi-disciplinary teams to cooperate and participate in the conceptualisation phase. Thus, the project proposes a multi-dimensional, multi-level, and multi-layer framework model that covers the whole space of solution to the problem. In addition to civil engineers with expertise in construction management and IT; academicians working in the field of architecture with expertise in construction management, IT, architectural philosophy, architectural history, and conservation; academicians working in the field of interior architecture with experience in designing entities at the building premises level; academicians working in the field of urban and region planning with expertise in sustainability – the whole research team contributed to the design of SIMURG conceptual and practical models.

SIMURG assumes that information required for sustainability assessment has been previously organised in databases of various governmental offices in Turkey and proposes to integrate the fragmented information. Therefore, as a local solution, these Turkish country-specific databases are accepted as external plugins of the SIMURG core conceptual model. This will enable determining the relational database architecture and the relationships of peripheral components. Extending the model from a local to a global scale is the goal to be achieved during the implementation phase and interoperability of country-based systems is necessary to benchmark countries in terms of their performances of sustainability using the 3D Cartesian system.

Dashboards for representing the performance of entities/facts in the dimensions of the 3D Cartesian system of environmental sustainability are developed by international institutions on digital platforms. These solutions are not comprehensive enough and do not support case-based/citizen-centric/multi-part interactive assessment processes for determining the most suitable options that meet the expectations of citizens regarding the professional, social, and built environment. In this paper, SIMURG, which is the most comprehensive model developed for the performance-based assessment of not only entities in the built environment dimension but also entities and facts in the other two dimensions of the 3D Cartesian system, is converted to a practical (software) model. It is obvious that such a model requires the approval of high-level public authorities on both a local and a global scale, and for this reason, the implementation of SIMURG will be a difficult process. Contemporary digital technology is potent enough to manage these comprehensive models and even more complicated ones that would include artificial intelligence functions. A new era called Society 5.0 has just started, supported by digital tools that are currently being made available to fulfil a citizen-centric vision. As soon as the resistance of the construction industry is overcome, we will witness the consequences of these efforts.

7. Conclusions

The paradigmatic model of SIMURG proposes a human-centric governance approach and follows sustainable development goals (SDGs) defined by the UN. The framework model proposes a 3D Cartesian system as a representation of the dimensions of sustainability. The organisational model is based on a distributed system of roles and functions and proposes rethinking these roles and relationships by considering functions of information providers and accredited labs and institutions in the certification process of built environment entities, which covers particular aspects of their design. The integrational/interoperability model proposes integration/interoperability of public information sources. OmniClass information classification system and BIM 6D tools are proposed as means of organising information needed in the built environment dimension. The calculation model is based on a solar system simulation algorithm that is inspired by the gravity equation and performance-based assessment. And finally, the computer model is based on lean relational database architecture that allows the required information sources to be plugged into the frame model.

The master project and its components are currently being conducted in the research lab SIMURG_ALKU & ITU, by both institutions: Alanya Alaaddin Keykubat University (ALKU) and Istanbul Technical University (ITU). The study aims to examine the structure and relationships of an integrated model which will be useful to individuals, institutions, and public authorities operating in the construction sector in making decisions concerning built environment entities. Accordingly, that performance-based approach can be applied in a significant part of industry as a valid and effective approach. Further studies that include all the necessary dimensions of the sustainability assessment problem and address the issue of putting conceptual models into practice are required more than ever.

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