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EXPERT CAUSE AND EFFECT ANALYSIS OF THE FAILURE OF HISTORICAL STRUCTURES TAKING INTO ACCOUNT FACTORS THAT ARE DIFFICULT TO MEASURE

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The protection of Polish architectural heritage in the former eastern borderlands, accomplished through the conservation and technical securing of historical structures, constitutes one of the main programmes that are implemented by the Ministry of Culture and National Heritage. Currently, many Polish historical buildings in the former eastern borderlands are in a very bad technical condition. The load-bearing systems of these elements, as well as elements of their finish, require immediate emergency securing work. The basic steps that precede conservation work are emergency structural works, which guarantee the durability and stability of the entire historical substance. The specifics and complexity of the problem of the failure of historical buildings often demands an in-depth analysis of a series of factors that are difficult to measure and which are responsible for the cause and effect relationship during the early stage of the technical evaluation of a structure. The analyses of failures of numerous historical structures, for instance that were carried out by the authors, have become the inspiration for the search for effective methods of analysis that would allow for an in-depth analysis of the causes and effects of the failures in question. The DEMATEL method (Decision Making Trial and Evaluation Laboratory) that has been presented in this work, and its fuzzy extension, has lately become one of the more popular methods used in the cause-and-effect analysis of various phenomena. The authors demonstrated how this method works on the example of the evaluation and securing of the load-bearing system of the XVII Collegiate church of the Holy Trinity in the town of Olykha in the Volhynskiy Oblast, Ukraine.

Keywords: cause-and-effect analysis, DEMATEL (Decision Making Trial and Evaluation Laboratory), fuzzy logic, failure of a historical structure.

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1. INTRODUCTION

The failures of buildings, especially historical structures, require an in-depth cause-and effect-analysis of the occurrence of damage and determining the manner of their repair. The problems that need to be tackled by specialists from many technical fields, including construction engineers, often exceed the bounds of standard construction or design solutions. The specifics of a historical structure require the carrying out of an evaluation of the phenomena that influence the damage that has appeared. The structural problems associated with historical structures were the subject of numerous publications, e.g.,[1, 11] that were presented at scientific conferences. In order to synthetically describe and analyse the problem above, it is necessary to select the proper tool that can enable the appropriate modelling and analysis of the considered dependencies between elements. The concept of a system made up of two elements, between which there are certain relationships (dependencies) are at the foundation of many analysis methods. One of the effective concepts of representing such a system is structural modelling, which makes it possible to understand the properties of complicated systems [20]. We can find many methods used in the modelling and analysis of various problems in subject literature [12,13,15,16,21]. One of the more popular methods of structural modelling is the DEMATEL method (Decision Making Trial and Evaluation Laboratory), which was developed by A. Gabus and E. Fontela [8] and serves chiefly to model and analyse cause-and-effect phenomena. This method is, according to the authors, the proper tool to be used in the analysis of the technical problem discussed in this paper. We can find many examples of the use of the DEMATEL method to analyse cause-and-effect phenomena in building construction in literature, for instance [5,6,7]. In the positions mentioned above, the uncertainty of experts' evaluations are not taken into account, which is important in the case of phenomena that occur in a historical building that are difficult to measure. Taking into account the fact, that the complexity of the problem and the precision of its analysis occur in an inverse dependency [4], then, as a consequence, the imprecision of the data is going to affect the uncertainty and disparity of the evaluations in the opinions of experts that take part in an analysis. This is why the authors of this paper propose the adoption of an extension of the DEMATEL method by introducing elements of fuzzy logic into its algorithm in order to take into account the uncertainty of experts' opinions and the aggregation of discrepant opinions in the analysis [10,17,18,19].

2. EXAMPLE OF THE USE OF THE SELECTED METHOD OF STRUCTURAL MODELLING FOR THE PURPOSES OF A CAUSE-AND-EFFECT ANALYSIS OF THE FAILURE OF A HISTORICAL STRUCTURE

2.1. THE DEMATEL METHOD AND ITS FUZZY EXTENSION

In the DEMATEL method (Decision Making Trial and Evaluation Laboratory), the tool used to model the dependencies between the elements of a system is a directed graph (fig. 1), the points of which symbolise the elements of the system, while the arches define the relationships (effects) between these elements.

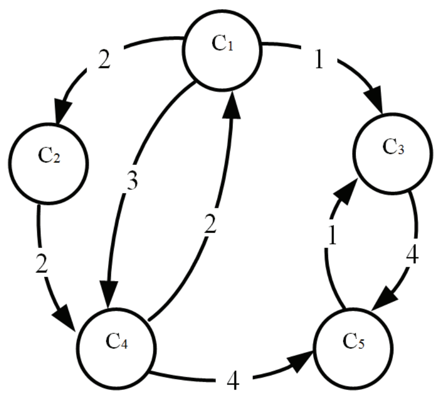

Fig. 1. A sample direct influence graph with numerical influence intensity markers between the elements of a system.

The evaluation of the direction and intensity of influence between these elements is carried out by experts with the help of a five-degree verbal scale, to which numerical values are assigned. These values are then introduced into a matrix, in which the sum of all of its exponents in the liminal sense returns the exit values within the analysed model.

Below, on the basis of [3, 9], the procedure of the use of a fuzzy extension of the DEMATEL has been presented, which can be used to perform a cause-and-effect analysis of the failures of historical structures.

Step 1. The construction of the structure of the model is initially based on determining the set of the elements of the system, which are going to have their direct relationships established in the next step.

Step 2. A group of experts evaluates the direction and intensity of the mutual influence that occurs between the elements in a linguistic manner. The depiction of the relationships between the elements of the system is going to be a directed graph of direct influence. To this end, they use a linguistic evaluation scale contained in table 1, the fuzzy representation of which are triangular fuzzy numbers in accordance with fig.2.

The proposed triangular shape of the membership function for the fuzzy number is its basic shape and is often used in such types of expert analyses. The change of the membership between parameters of the same function is a linear interpolation, which reflects the intuitive character of the formulation of expert opinions in a simple manner.

Table 1.The linguistic evaluations of the influence of an element and their depiction in the form of triangular fuzzy numbers.

Assessing the influence of the element in the system	
Assessment of linguistic	Triangular fuzzy numbers
No influence (NI)	(0, 0, 0.25)
Low influence (LI)	(0, 0.25, 0.5)
Average influence (AI)	(0.25, 0.5, 0.75)
High influence (HI)	(0,5, 0,75, 1)
Very high influence (VHI)	(0,75 1, 1)

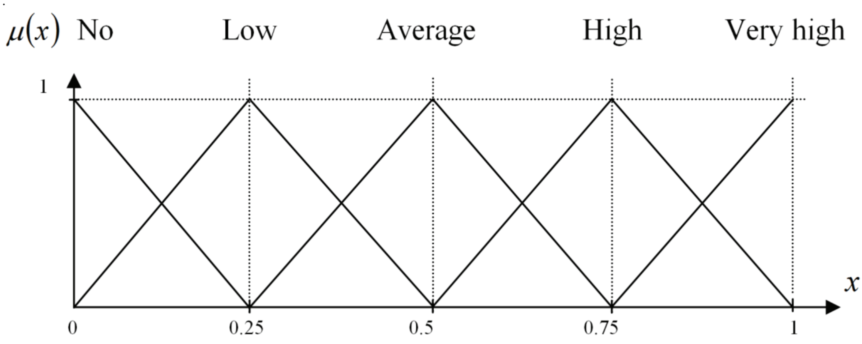

Fig.2. The linguistic space for linguistic variables determining the influence of the element of a system, source: based on: [14]

The use of triangular fuzzy numbers in this procedure requires the defining of the arithmetical calculations on such numbers.

Arithmetical calculations on any two triangular fuzzy numbers $\tilde{a}_{11} = (l_{11}, m_{11}, u_{11})$ i $\tilde{a}_{12} = (l_{12}, m_{12}, u_{12})$ are hence as follows [3]:

(2.1) $$\tilde{a}_{11} \oplus \tilde{a}_{12} = (l_{11} + l_{12}, m_{11} + m_{12}, u_{11} + u_{12})$$

(2.2) $$\tilde{a}_{11} \ominus \tilde{a}_{12} = (l_{11} - l_{12}, m_{11} - m_{12}, u_{11} - u_{12})$$

(2.3) $$\tilde{a}_{11} \otimes \tilde{a}_{12} = (l_{11} l_{12}, m_{11} m_{12}, u_{11} u_{12})$$

(2.4) $$\lambda \otimes a_{11} = (\lambda l_{11}, \lambda m_{11}, \lambda u_{11})$$

Step 3. The effect of the evaluations performed by experts is a set of partial fuzzy matrices $\tilde{X}_k = \{\tilde{a}_{ijk}\}$, $i, j = 1, \ldots, n,\ k = 1,2, \ldots, K,$ of direct influence, where: $\tilde{a}_{ijk} = (l_{ijk}, m_{ijk}, u_{ijk})$ are fuzzy numbers with a triangular membership function $\mu_{\tilde{a}_{ijk}}(x) \in [0,1]$ that express the fuzzy assessment of the relationship of element *i* and *j*, expressed by expert $k = 1,2, \ldots, l$.

(2.5) $$\tilde{X}_k = \begin{bmatrix} \tilde{a}_{11k} & \tilde{a}_{12k} & \ldots & \tilde{a}_{1nk} \\ \tilde{a}_{21k} & \tilde{a}_{22k} & \ldots & \tilde{a}_{2nk} \\ \ldots & \ldots & \ldots & \ldots \\ \tilde{a}_{n1k} & \ldots & \ldots & \tilde{a}_{nnk} \end{bmatrix}$$

The main diagonal of matrix $\tilde{X}_k$ is going to be the location of elements $\tilde{a}_{ijk}$, $i, j = 1, \ldots, n, i \neq j$, $k = 1,2, \ldots, K$ which determine the influence between the elements of a system.

Step 4. The normalisation of the direct influence matrix $\tilde{X}_k$ should be carried out in accordance with the formula below:

(2.6) $$\bar{\tilde{X}}_k = \frac{1}{\lambda_k} \otimes \tilde{X}_k$$

The normalising value λ_k is calculated as the maximum sum of the row of the upper parameters u_{ijk} elements $\tilde{a}_{ijk}$ of the $\tilde{X}_k$ fuzzy matrix.

(2.7)

$$\lambda_k = \max_{i=1,\dots,n} \left\{ \sum_{j=1}^{n} a_{ijk} \right\}$$

As a result, each element of the normalised direct influence matrix $\tilde{C}_k$ will take on the form of a three-dimensional vector:

(2.8)
$$\bar{\tilde{a}}_{ijk} = \left(\frac{l_{ijk}}{\lambda_k}, \frac{m_{ijk}}{\lambda_k}, \frac{u_{ijk}}{\lambda_k} \right)$$

Step 5. On the basis of the direct influence matrix $\bar{\tilde{X}}_k$ we should determine the resultant total influence matrix $\tilde{T}_k = \{\tilde{t}_{ijk}\}$ where: $\tilde{t}_{ijk} = \left(t_{ijk}^{(l)}, t_{ijk}^{(m)}, t_{ijk}^{(u)} \right)$, the interpretation of which is as follows:

(2.9)
$$\tilde{T}_k = \bar{\tilde{X}}_k \oplus \widetilde{\Delta T}_k$$

where: $\widetilde{\Delta T}_k = \bar{\tilde{X}}_k^2 \oplus \bar{\tilde{X}}_k^3 \oplus \dots \bar{\tilde{X}}_k^p$ is an indirect influence matrix, which is the sum of the successive exponents of direct importance-influence matrices $\bar{\tilde{X}}_k$

Using the relation $\lim_{p\to\infty} \bar{\tilde{X}}_k^p = [0]_{nxn}$, the total influence matrix can be calculated based on the relation:

(2.10)

$$\tilde{T}_k = \sum_{p}^{\infty} \bar{\tilde{X}}_k^p = \bar{\tilde{X}}_k \left(I \ominus \bar{\tilde{X}}_k \right)^{-1}$$

Where I is a unit matrix.

Because the evaluation of influence is done by a group of k-experts, a k-amount of total influence matrices with fuzzy elements described by triangular membership functions $\mu_{\tilde{t}_{ijk}}(x) \in [0,1]$ will be designated.

Step 6. In order to aggregate partial expert's opinions, we need to use an arithmetic mean fuzzy operator in accordance with the formula below [3]:

(2.11) $$\tilde{T} = \frac{(\tilde{T}_1 \oplus \tilde{T}_2 \oplus \ldots \oplus \tilde{T}_K)}{K}$$

Hence, the fuzzy, aggregated total influence matrix is going to take on the following form:

(2.12) $$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \ldots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \ldots & \tilde{t}_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ \tilde{t}_{n1} & \ldots & \ldots & \tilde{t}_{nn} \end{bmatrix}$$

where $\tilde{t}_{ij} = \sum_{k=1}^{K} \tilde{t}_{ijk}/K$, are fuzzy numbers with a triangular membership function $\mu_{\tilde{t}_{ij}}(x) \in [0,1]$

Step 7. The matrix obtained as the result of the aggregation requires defuzzification using a chosen method of defuzzification. In the example at hand, the authors propose that the Centre of Gravity (COG) method be used for defuzzification [22].

(2.13) $$t_{ij} = t_{ij}^{(m)} + \frac{t_{ij}^{(u)2} + 2 \cdot t_{ij}^{(m)} \cdot \left(t_{ij}^{(l)} - t_{ij}^{(u)}\right) - t_{ij}^{(l)2}}{3 \cdot \left(t_{ij}^{(u)} - t_{ij}^{(l)}\right)}$$

where: t_{ij} is a crisp value of an element of the aggregated matrix $\widetilde{\mathrm{T}}$,

Step 8. The total influence matrix T obtained in the manner above constitutes the basis for the obtaining of the final results of the cause-and-effect analysis by determining the total influence value r_i of element i and its total susceptibility c_i in accordance with the relations below:

(2.14)

$$r_i = \sum_{j=1}^{n} t_{ij}$$

(2.15)

$$c_i = \sum_{j=1}^{n} t_{ji}$$

The sum of values r_i and c_i determines the total engagement of system element i, while the difference informs us of the role of this element within the system. A positive value of the difference $r_i - c_i$ states that element i has a causal character, while a negative value informs us that it is an effect. The absolute value of the difference $r_i - c_i$ determines the strength of the abovementioned causal (effectual) character of the analysed element.

In order to simplify the analysis of the relationships between the elements of the analysed system, the values that have been obtained should be depicted in a graphical manner within a two-dimensional coordinate system, creating a so-called impact-relation map - IRM. The value of the sum $r_i + c_i$ is going to be placed on the axis of abscissae, while the value of the difference $r_i - c_i$ on the axis of ordinates.

In order to determine the net values of the total influence of the elements of the system in question, we can make use of the following dependency: [2, 6, 9,].

(2.16)

$$\Delta_{t_{ij}} = \begin{cases} t_{ij} - t_{ji} & if \quad t_{ij} > t_{ji}, \\ 0 & if \quad t_{ij} \le t_{ji} \end{cases}$$

As a result, the cause-and-effect relationships between the elements of the system will be depicted in the form of a total net impact map, which will be represented in the form of a total net impact directed graph.

2.2. A cause-and-effect analysis of the failure of the Holy Trinity Collegiate Church in Olykha, Volhynskiy Oblast, Ukraine.

One example of a historical building that depicts a massive scale and type of damage is the Holy Trinity Collegiate Church in the locality of Olykha in Volhynskiy Oblast, Ukraine (Fig. 3). The church was built in the years 1635-1640 and was commissioned by Albrecht Stanisław Radziwił, to be built in the same manner as the Il Gesù Church (it is also stylistically tied with the Church of the Annunciation of the Holy Virgin Mary in Grodno). It was regarded as the most beautiful temple of Volhynia, often described as the "Pearl of Volhynia". The designers of the church were Italians: Benedetto Molli and Giovanni Maliverna. The sculptors Melchior Erlenberg and Michał Germanus also had their share in the erection of the church. The church was consecrated in 1640 by bishop Andrzej Gębicki, being elevated to the rank of a collegiate church a year later. In 1638, the founder of the church established a college near the church - a branch of the Zamojski Academy, as well as a seminary. The collegiate chapter house existed in Olykha until the year 1945. After the year 1945, the church was closed to the Catholic parish and, mostly deliberately, ruined and adapted to be used as a storehouse. In the beginning of the 1990's, due to a change in the geo-political situation, the Collegiate Church was returned to the Roman Catholic parish belonging to the Łuck diocese. In 2013, the authors of the paper performed a series of analyses with the goal of evaluating the load-bearing system and the causes of the damage that threatened the safety of the structure.

Fig. 3. The Collegiate Church of the Holy Trinity in Olykha, Ukraine, view from the south.

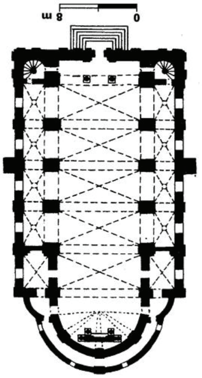

Fig. 4. Floor plan of the Collegiate Church in the Volhynskiy Oblast

The structural layout of the Collegiate Church resembles the typical system used in historical buildings from the Baroque period. The floor plan of the building (fig. 4) is composed of a main nave, which ends with a semicircular presbytery in the south, and two side naves. The length of the Collegiate Church is around 45 m, while its width is around 15 m. Above the main nave and the side naves there are brick groin vaults without sand fills. The vaults of the main naves were rebuilt many times over the course of the last few centuries, which was confirmed by the varied thickness of the vaults. Above the vault of the main nave there is a modern steel structure of the roof, in the form of four identical trusses, while above the side naves there are pulpit roofs, supported by a load-bearing system composed of a timber structure. The original support structure of the roof above the main nave was also a timber system. Unfortunately, as a result of a failure due to a fire that consumed the roof, the entire load-bearing system was destroyed. Currently, the cladding of the roof of the entire Collegiate Church (the main nave and side naves) is made of steel sheets. The floor of the Collegiate Church of the Holy Trinity has also been constructed in the form of brick vaults with sand fills. Beneath the entire Collegiate Church (the main and side naves) are the former burial crypts (including the former resting places of the Radziwił family), of varying height and finish. The outer walls of the church have a thickness ranging from around 1,8 m to 2,3 m and were made entirely from ceramic elements - solid bricks with dimensions around 7 cm x 27 (28 cm) x 13 cm, which are typical of historical ceramic bricks. The walls of the underground section are of a similar width and are made from the same material as the surface part.

An analysis conducted by the authors of this paper in 2013 uncovered numerous instances of damage in the form of cracks and marks of a structural nature, which can be considered typical of historical buildings. The scale of the damage in the building of the collegiate church is depicted in figs. 5, 6, 7, 8.

Fig. 5. A view of the cracks and marks on the vault ceiling (photograph to the left), as well as a close-up of the damage (photograph to the right)

Fig. 6. A view of the damage of the interior wall from inside the building (photograph to the left) as well as a close-up of a visible crack in the structure of the wall (photograph to the right).

Fig. 7. The photograph depicts the building from the eastern side (photograph to the left). Visible damage of the abutment of the wall, along with the material and structural degradation of the wall (photograph to the right).

The development of the technical documentation of the revalorisation and securing of the building of the historical Collegiate Church required the performing of a cause-and-effect analysis of the cause of the damage. To this end, the basic, potential factors of the failure of the structure in question have been established, the description of which is as follows:

a) **factor C_1** - The lack of wall cladding in the form of plaster on either side (both on the interior and exterior side).

b) **factor C_2**- The deliberate damaging of the abuttments of the exterior walls (loss of the spatial rigidity of the system) (figs.: 7,9),

c) **factor C_3**- The biological corrosion of the walls in the form of moss and lichen growths. (figs.: 7, 8).

d) **factor C_4** - The weakening of the structure of the mortar or loss of mortar in the bindings between the bricks. (fig. 11),

e) **factor C_5** - Excessive moisture within the walls resulting from capillary action (figs.: 8, 11).

f) **factor C_6** - The fire of the roof along with failure in the form of the collapse of the timber roof structure above the main nave of the Collegiate Church (fig. 10).

g) **factor C_7** - The vertical and horizontal displacement of the external walls.

h) **factor C_8** - The time of the building's construction - the first half of the XVII century,

i) **factor C_9** - The influence of climatic factors, such as: rain, snow, high and low temperatures - thermal deformation of the vault.

Factor C_{10} is associated with the cracks and scratch marks on the vaulted ceilings and brick walls, which makes it an effect of these factors.

Fig. 8 View of the facade from the eastern side of the building, biological corrosion of the walls

Fig. 9. A damaged abuttment.

Fig. 10. View of the vault of the main nave walls after the failure associated with the collapse of the structure of the roof due to a fire that occurred in the past.

Fig. 11. Losses of mortar within the brick structure of the

Using a systemic approach to the performing of a cause-and-effect analysis, the failure factors mentioned before will be the elements of the analysed system.

In accordance with the procedure outlined in chapter 2.1, a five-man group of experts was assembled, with knowledge regarding building construction, including knowledge about the analysed structure and experience in determining the cause of and eliminating the effects of the failure of historical structures. The experts analysed the potential factors of the failure of the structure in question and performed an evaluation of the dependencies between them, in addition to determining their impact on the technical condition of the vault.

According to the procedure, the experts evaluated the dependencies above in a linguistic manner. For instance, table 2 provides the opinions provided by one of the experts.

Table 2. Linguistic evaluations of the relationships between the elements of the system.

Expert 1	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	-	NI	AI	VHI	HI	NI	LI	NI	AI	LI
C_2	NI	-	NI	NI	NI	NI	VHI	AI	NI	VHI
C_3	HI	NI	-	HI	HI	HI	HI	NI	AI	AI
C_4	NI	NI	HI	-	AI	AI	HI	HI	HI	HI
C_5	LI	NI	HI	VHI	-	NI	HI	NI	HI	HI
C_6	NI	NI	HI	NI	NI	-	VHI	LI	AI	VHI
C_7	LI	VHI	NI	NI	LI	VHI	-	AI	VHI	VHI
C_8	LI	AI	HI	HI	LI	LI	AI	-	NI	LI
C_9	AI	NI	AI	HI	HI	AI	VHI	LI	-	VHI
C_{10}	NI	NI	NI	NI	NI	NI	NI	NI	NI	-

The use of the aforementioned calculation procedure allows us to obtain a resultant, aggregated, fuzzy total influence matrix of the elements within the system. As a result of the defuzzification of the abovementioned matrix, we are provided with the crisp values of their elements - table 3.

Table 3. The final total influence matrix of the elements within the system

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	0.103	0.097	0.202	0.257	0.202	0.068	0.172	0.116	0.156	0.175
C_2	0.123	0.059	0.149	0.184	0.116	0.073	0.222	0.122	0.102	0.247
C_3	0.182	0.098	0.134	0.243	0.207	0.095	0.210	0.121	0.140	0.196
C_4	0.170	0.110	0.218	0.157	0.211	0.088	0.244	0.145	0.151	0.236
C_5	0.168	0.103	0.240	0.264	0.123	0.073	0.210	0.114	0.142	0.213
C_6	0.139	0.098	0.173	0.227	0.141	0.059	0.233	0.103	0.178	0.269
C_7	0.131	0.114	0.154	0.203	0.139	0.093	0.127	0.136	0.135	0.246
C_8	0.202	0.138	0.241	0.280	0.221	0.105	0.252	0.099	0.173	0.244
C_9	0.162	0.113	0.210	0.254	0.199	0.087	0.253	0.122	0.104	0.268
C_{10}	0.044	0.035	0.051	0.056	0.048	0.033	0.055	0.039	0.043	0.046

The values of the total impact and relations, and the total activity and role of a given element within the system are presented in table no. 4.

Table 4. The values of the total influence and susceptibility, as well as the total engagement and role of the elements within the system.

	r	c	$r+c$	$r-c$
C_1	1.548	1.424	2.972	0.124
C_2	1.396	0.964	2.360	0.432
C_3	1.626	1.771	3.397	-0.144
C_4	1.729	2.127	3.856	-0.398
C_5	1.651	1.608	3.259	0.042
C_6	1.620	0.773	2.393	0.847
C_7	1.478	1.978	3.456	-0.499
C_8	1.957	1.118	3.075	0.839
C_9	1.772	1.325	3.096	0.447
C_{10}	0.450	2.140	2.590	-1.690

The impact-relations map for the factors that determine the failure of the structural system, as well as the total net influence graph, are presented, by figures 11 and 12, respectively.

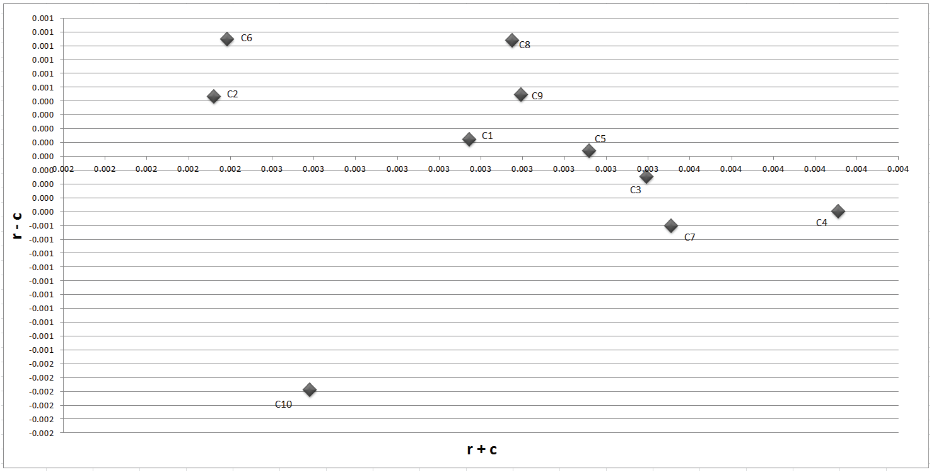

Fig. 11. The impact-relations map of the elements within the system.

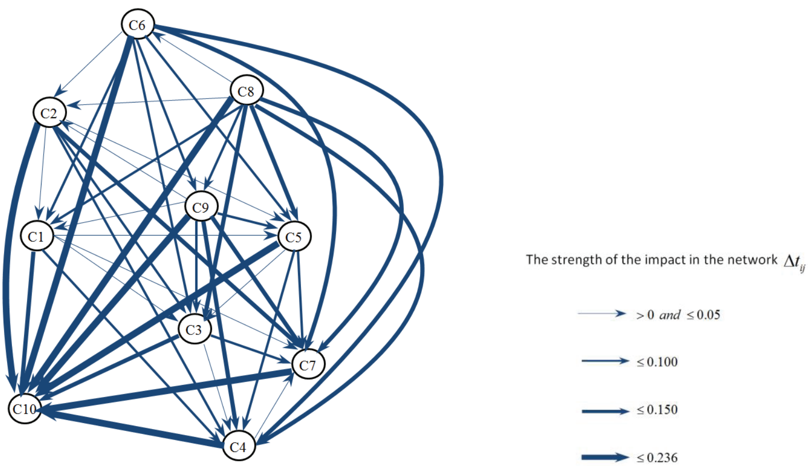

Fig. 12. The graph of the total net influence of the elements of the system.

The results that were obtained should be interpreted in the following manner:

The most dominant factors of a causal character (the highest positive value of the difference $(r_i - c_i)$ are: factor C_6 - the fire on the roof and, as a consequence, the loss of the load-bearing capacity of the main structural elements of the building and C_8, which is the age of the building. Further in the order of the causes of the damage of the vaults and walls of the collegiate church are climatic factors causing the thermal warpage of the vaults C_9 and the deliberate damaging of the abuttments of the external walls C_2

that have an influence on the vertical and horizontal displacements of the external walls and, as a consequence, the occurrence of damage on the aforementioned walls and vaults. The factors associated with the lack of a barrier on the walls in the form of plaster C_1, constitutes, in comparison to the abovementioned factors, a decidedly marginal cause of the damage of the vaults and walls of the building. The excessive moisture within the walls due to capillary action C_5 has, as a factor, the lowest positive role indicator $r_i - c_i$, the value of which is close to zero and which can indicate its neutral causal or effectual character in relation to the damage to the walls and vaults. The factors C_3, C_4, C_7, C_{10} have a negative role indicator, which means that they are the effects of the influence of other factors, which confirms that the largest susceptibility to influence has been observed in the case of factor C_{10}, associated with the cracks and marks on the vaults and brick walls of the analysed building. Apart from the observations stated above, it would be good to take a look at the individual engagement of each factor in the cause-and-effect analysis. In this regard, factors $C_4, C_7, C_3,$ despite their effectual character, possess a higher total engagement than all the others (the highest value of the $r_i + c_i$ activity indicator). The total net influence graph constitutes a rounding out of the discussion above, as we can decipher the direction of the relationships between the factors and the intensity of total net influence from it. As a result, we can observe that the dominating factor is the age of the building, and the scratches of the vaulted ceilings and brick walls constitute an effect of the indirect and direct influences that are analysed in the paper, as well as other factors,

Conclusion:

The carrying out of emergency work on historical buildings demands the prior development of specialist technical and structural documentation which takes into account the typology of the damage and an analysis of the load-bearing system. Historical buildings, due to their "age", as well as distinct structural solutions, require individual research and analysis. The inclusion of atypical forms of destructive influence on a building, as well as the specific human activity in the form of devastation is an absolute necessity in such cases. The development of technical documentation containing practical guidelines for the securing and revalorisation of the historical substance of buildings needs to be preceded by a cause-and-effect analysis of the damage seen in those structures. An attempt at synthetically describing the above problem and framing it in the form of a system composed of various elements between which certain relationships occur can be considered good practice. In addition, due to the character of the elements of such a system (which are difficult to measure), it is necessary to take into account the problem of uncertainty and the aggregation of the evaluations performed by experts taking part in the analysis. The DEMATEL method (Decision Making Trial and Evaluation

Laboratory) proposed in the paper, along with its fuzzy extension, can be used to analyse a problem that has been defined in this manner. The results that were obtained with the use of the abovementioned procedure to perform a cause-and-effect analysis of the load-bearing system of the XVII-century Collegiate Church of the Holy Trinity in Olykha, Volhynskiy Oblast, Ukraine, have confirmed the effectiveness of the above method. An in-depth interpretation of the results of the presented analysis had made it possible to develop a detailed structural design of the reinforcement of the main load-bearing elements of the analysed building. The scope of the necessary - and, at the same time, properly selected - technical solutions, which refer only to the basic factors (the causes of the failure) will make it possible to limit construction work on the Collegiate Church to the necessary minimum, while allowing the provision of the complete stability of the structure. Indeed, it is necessary to respect the regulations of the Athens Charter [23] regarding modifications to historical substance, which must focus on preserving the durability of a structure by performing only the necessary construction work.

REFERENCES

[1] A. Adjukiewicz i in., „Awaria wielkopołaciowego dachu o konstrukcji drewnianej" – XXIII konferencja naukowo-techniczna „Awarie Budowlane", 2007

[2] P.-Y. Chen, C.-C. Chang, "The analysis of service acceptance framework for social games based on extensive technology acceptance model", [w:] Proceedings of PICMET '10: Technology Management for Global Economic Growth (PICMET), pp. 1–11, 2010.

[3] L. Chi-Jen, W. Wei-Wen, "A causal analytical method for group decision-making under fuzzy environment", Expert Systems with Applications, 34, pp. 205–213, 2008.

[4] J. Chojean, J. Łęski, „Zbiory rozmyte i ich zastosowania", Wydawnictwo Politechniki Śląskiej, Gliwice, 2009.

[5] M. Dytczak, G. Ginda, T. Wojtkiewicz, „Analiza związków przyczynowo-skutkowych w awarii konstrukcji przekrycia zbiornika", W: Materiały XXV Konferencji Naukowo-Technicznej „Awarie budowlane". Szczecin-Międzyzdroje, 2011a.

[6] M. Dytczak, G. Ginda, „Wybrane wielokryterialne metody wartościowania uwzględniające trudno mierzalność cech zabytków", pod redakcją B. Szmygina, „Systemy wartościowania dziedzictwa - stan badań i problemy", Lubelskie Towarzystwo Naukowe, Międzynarodowa Rada Ochrony Zabytków ICOMOS Politechnika Lubelska, Warszawa, pp. 39-59, Lublin 2015.

[7] M. Dytczak, G. Ginda, "Identyfication of building Repair policy choice criteria role. Technological and Economic Development of Econom", Baltic Journal on Sustainability, pp. 213-228, 2009a.

[8] A. Gabus, E. Fontela, "World Problems an Invitation to Further Thought within the Framework of DEMATEL", Battelle Geneva Research Centre, Switzerland Geneva 1972.

[9] G. Ginda, M. Maślak, „Wybrane metody analizy eksperckiej w wielokryterialnej ocenie parametrów determinujących bezpieczeństwo w pożarze", Politechnika Krakowska, Kraków 2010.

[10] N. Ibadov, J. Rosłon, "Technology Selection For Construction Project, With The Use Of Fuzzy Preference Relation", Archives of Civil Engineering, 61, (3), pp. 105-118, 2015.

[11] Z. Janowski wraz z zespołem, „Analiza oraz naprawa i rekonstrukcja sklepień w obiektach historycznych", 2007, ISBN 978-83-7457-029-9

[12] MV Ksiażek, P. Nowak, S. Kivrak, JH, Roslon, L. Ustinovichius, Computer-aided decision-making in construction project development , Journal of Civil Engineering and Management, 21 (2), pp. 248-259, 2015.

[13] M. Książek, P. Ciechowicz, Selection of the General Contractor Using the AHP Method, Archives of Civil Engineering, 62 (3), pp. 105-116, 2016,

[14] R. J. Li, "Fuzzy method in group decision making". Comp. and Math. with App., 38 (1), pp. 91–101, 1999.

[15] J. Michnik, „Wielokryterialne metody wspomagania decyzji w procesie innowacji", Uniwersytet Ekonomiczny w Katowicach, Katowice 2013

[16] P. Nowak, M. Skłodkowski, Multicriteria Analysis of Selected Building Thermal Insulation Solutions, Archives of Civil Engineering, 62 (3), pp. 137-148, 2016.

[17] E. Radziszewska-Zielina, "Fuzzy control of the partnering relations of a construction enterprise", Journal of Civil Engineering and Management, 17(1), pp. 5-15, 2011.

[18] E. Radziszewska- Zielina, G. Śladowski, "Fuzzy inference system assisting the choice of a variant of adaptation of a historical building", International Journal of Contemporary Management 14/4, pp. 131-148, 2015.

[19] E. Radziszewska-Zielina, B. Szewczyk, "Controlling partnering relations in construction operations using fuzzy reasoning", Archives of Civil. Engineering, 1 (3), pp. 89-104, 2015.

[20] F.S. Roberts, "Applications of the theory of meaningfulness to psychology", Journal of Mathematical Psychology, 29(3), pp. 311-332, 1985.

[21] J. Rosłon, M. Seroka, Multicriteria Selection of Water Insulation Technology for Foundation Walls in an Existing Building, Archives of Civil Engineering, 62 (3), pp. 167-176, 2016.

[22] R. Yager, D. Filev, "Essentials of Fuzzy Modeling and Control", John Wiley & Sons, New York, 1994

[23] The Athens Charter for the Restoration of Historic Monuments – 1931

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EKSPERCKA ANALIZA PRZYCZYNOWO-SKUTKOWA AWARII ZABYTKOWYCH OBIEKTÓW BUDOWLANYCH Z UWZGLĘDNIENIEM CZYNNIKÓW TRUDNOMIERZALNYCH

Słowa kluczowe: analiza przyczynowo-skutkowa , DEMATEL (Decision Making Trial and Evaluation Laboratory), logika rozmyta, awaria obiektu zabytkowego

STRESZCZENIE:

W artykule przedstawione zostało zagadnienie związane z analizą przyczynowo-skutkową awarii obiektów zabytkowych z uwzględnieniem czynników trudnomierzalnych Przeprowadzone przez autorów artykułu analizy uszkodzeń wielu obiektów zabytkowych stały się przyczynkiem do poszukiwania efektywnych metod analizy, które pozwolą na wstępną, wnikliwą identyfikację przyczyn i skutków związanych z awarią tego typu obiektów. Zaproponowana w pracy metoda DEMATEL (Fuzzy Decision Making Trial and Evaluation Laboratory) jest ostatnio jedną z bardziej popularnych metod używanych do analizy przyczynowo-skutkowej różnych zjawisk. Metoda ta zdaniem autorów niniejszego artykułu jest właściwym narzędziem służącym do analizy zawartego w pracy problemu technicznego. W literaturze można znaleźć wiele przykładów zastosowania metody DEMETEL do analizy zjawisk przyczynowo skutkowych w budownictwie np. [5,6,7]. W powyższych pozycjach nie uwzględnia się jednak niepewności ocen eksperckich, która w przypadku badania zjawisk trudnomierzalnych zachodzących w obiekcie zabytkowym jest istotna. Dlatego w celu uwzględnienia w analizie niepewności eksperckich ocen oraz agregacji rozbieżnych opinii autorzy niniejszego artykułu zaproponowali zastosowanie rozmytego rozszerzenia [3,9] metody DEMATEL poprzez wprowadzenie do jej algorytmu elementów logiki rozmytej [10,17,18,19]. Działanie powyższej metody autorzy zademonstrowali na przykładzie oceny i zabezpieczenia ustroju nośnego XVII wiecznej Kolegiaty p.w. Św. Trójcy w miejscowości Ołyka w Obwodzie Wołyńskim na Ukrainie.

W tym celu w pierwszej kolejności ustalono podstawowe, potencjalne czynniki awarii przedmiotowego obiektu, których opis jest następujący:

a) **czynnik C_1** - Brak osłony murów w postaci obustronnego tynku (po stronie wewnętrznej oraz zewnętrznej),
b) **czynnik C_2** - Celowe zniszczenie przypór ścian zewnętrznych (utrata sztywności przestrzennej ustroju) (Rysunki: 7, 9),
c) **czynnik C_3** - Korozja biologiczna murów w postaci rosnących na powierzchni mchów i porostów. (Rysunki: 7,8),
d) **czynnik C_4** - Osłabienie struktury zaprawy lub ubytki samej zaprawy murarskiej w wiązaniach pomiędzy cegłami. (Rysunek 11),
e) **czynnik C_5** - Ponadnormatywne zawilgocenie murów wynikające ze zjawiska podciągania kapilarnego (Rysunki: 8,11),
f) **czynnik C_6** - Pożar dachu wraz z katastrofą budowlaną polegającą na zawaleniu się więźby dachowej nad nawą główną Kolegiaty (rysunek 10),
g) **czynnik C_7** - Przemieszczenia poziome i pionowe murów zewnętrznych,
h) **czynnik C_8** - Wiek powstania budynku – 1 połowa XVII wieku,

i) **czynnik C_9** - Wpływ czynników klimatycznych takich jak: Deszcz, śnieg, wysoka i niska temperatura – Odkształcenia termiczne sklepienia.

j) **Czynnik C_{10}** - związany jest z pęknięciami i zarysowaniami sklepień oraz ścian ceglanych jest więc ostatnim ogniwem w ustalanym łańcuchu przyczynowo-skutkowym.

Następnie pięcioosobowa grupa ekspertów przeanalizowała potencjalne czynniki awarii przedmiotowego obiektu oraz dokonała oceny zależności pomiędzy nimi a następnie został określony ich bezpośredni wpływ na stan techniczny sklepienia oraz ścian murowanych przedmiotowego budynku. Ocena kierunku i intensywności wpływów bezpośrednich pomiędzy tymi czynnikami dokonana została za pomocą pięciostopniowej skali werbalnej, do której przypisane były liczby rozmyte. Liczby te wprowadzane zostały do macierzy, której suma wszystkich jej potęg w sensie granicznym zwracała wartości określające wpływy całkowite (bezpośrednie i pośrednie) czynników w analizowanym modelu. Otrzymane po defuzyfikacji rozmytej macierzy ostre wartości całkowitego wpływu i całkowitej podatności i w konsekwencji całkowitego zaangażowania i roli każdego z czynników posłużyły do stworzenia mapy znaczenia-relacji (impact-relation map – IRM) tych czynników (rysunek 11) Dodatkowo w oparciu o wyliczoną dla każdego czynnika wartości netto całkowitego wpływu [2,6, 9], wygenerowany został graf całkowitego wpływu netto pomiędzy czynnikami determinującymi awarie konstrukcji przedmiotowego budynku.

Analiza otrzymanych wyników z zastosowania powyższej procedury do analizy przyczynowo-skutkowej ustroju nośnego XVII wiecznej Kolegiaty p.w. Św. Trójcy w miejscowości Ołyka w Obwodzie Wołyńskim na Ukrainie potwierdziły efektywność powyższej metody.