Grzegorz Śladowski*
orcid.org/0000-0002-3452-8829

Wojciech Drozd**
orcid.org/0000-0001-7978-2268

Roman Paruch***, 1
orcid.org/0000-0002-4147-2245

Preliminary Cause-and-Effect Analysis of the Poor Technical Condition of a Historic Building Using Fuzzy Modeling and Structural Analysis

Wstępna analiza przyczynowo-skutkowa złego stanu technicznego budynku zabytkowego z wykorzystaniem rozmytego modelowania i analizy strukturalnej

Keywords: heritage building, technical condition, cause-and-effect analysis, FWINGS (Fuzzy Weighted Influence Nonlinear Gauge System), fuzzy logic

Słowa kluczowe: budynek zabytkowy, stan techniczny, analiza przyczynowo-skutkowa, FWINGS (Fuzzy Weighted Influence Nonlinear Gauge System), logika rozmyta

Introduction

The historic buildings located at the site of the former Auschwitz-Birkenau concentration and death camp in Oświęcim are the only ones of their kind on the UNESCO World Heritage List [Łopuska 2017]. In the case of the conservation of the masonry barracks in the oldest part of the former Auschwitz II-Birkenau concentration camp, the challenge was both the poor technical condition of the buildings, often equivalent to a state of structural failure, and the absence of a catalog of good practice and examples to follow [Paruch, Porębska 2026]. According to historical documents, the establishment of the Auschwitz II-Birkenau camp in Brzezinka dates to March 1941, with the first construction work carried out by Auschwitz prisoners and Soviet POWs in late 1941 and early 1942, using mostly materials sourced from demolition. The masonry barracks discussed here are located in the oldest part of the camp and, up to unprecedented conservation works conducted in 2019, they had not been opened to the public. These works were preceded by research conducted by a team from the Cracow University of Technology in cooperation with other Polish research institutions and the conservation team of the Auschwitz-Birkenau Museum [Celadyn et al. 2021; Paruch, Porębska 2026].

The pilot conservation project required, first of all, extensive and interdisciplinary analysis based on innovative non-destructive and low-impact testing and analysis of the buildings' state of preservation [Kańka et al. 2015] and the development of new conservation methods that could be applied in such a sensitive context. We should also note that fact that, in the case of heritage buildings, the procedure of analyzing adverse phenomena that occur within historic substance is highly complicated and complex due to

* *D.Sc. Ph.D. Eng., Cracow University of Technology, Faculty of Civil Engineering*
** *D.Sc. Ph.D. Eng., Cracow University of Technology, Faculty of Civil Engineering*
*** *Ph.D. Eng., Cracow University of Technology, Faculty of Architecture*

* dr hab. inż., Politechnika Krakowska, Wydział Inżynierii Lądowej
** dr hab. inż., Politechnika Krakowska, Wydział Inżynierii Lądowej
*** dr inż., Politechnika Krakowska, Wydział Architektury

Citation / Cytowanie: Śladowski G., Drozd W., Paruch R., Porębska A. Preliminary Cause-and-Effect Analysis of the Poor Technical Condition of a Historic Building Using Fuzzy Modeling and Structural Analysis. Wiadomości Konserwatorskie – Journal of Heritage Conservation 2026, 86:51–58

Otrzymano / Received: 20.09.2025 • **Zaakceptowano / Accepted:** 25.11.2025 **doi: 10.48234/WK86FUZZY**

Praca dopuszczona do druku po recenzjach *Article accepted for publishing after reviews*

the broad spectrum of factors with varying potentials for both structural and conservation impacts. The complex nature of this analysis requires the consideration of many internal and external factors that may affect the building. It is also necessary to consider the interdependent relationships between factors, which are often non-linear. In addition, the nature of this type of analysis often requires the processing of imprecise, incomplete or uncertain data. The uncertainty of the assessments or ratings by experts involved in the analysis and the need to aggregate their diverging opinions requires support in the form of sophisticated methods. The complexity of determining the impact of various factors on a building's poor technical conditions requires finding a means of initial, estimative and—most importantly—quick expert assessment that can be considered exploratory, to immediately take action to secure heavily damaged buildings before the findings of detailed investigations for complex repair measures become available.

Thus, the purpose of this article is to propose the FWINGS method as a systematic, qualitative approach, which considers the aforementioned specificity and can allow for an initial analysis of the impact of potential factors on a heritage building's technical condition before detailed analysis can be concluded. The operation of the above-mentioned method will be presented on the example of the prisoner barracks with inventory numbers B-123 and B-124 located in the BI section of the former Auschwitz-Birkenau concentration and extermination camp in Oświęcim.

Main model

According to systems theory, any decision problem can be interpreted as a system of decomposed elements, at least some of which can be interrelated. Structural modeling and analysis are foundational concepts for mapping such systems as they allow us to understand their complexity. The directed graph, whose vertices represent a system's elements (factors), and whose edges define relations (impacts) between the elements, is an essential tool used in system modeling. The construction of the inter-element relationship structure is based on the opinions of experts who take part in the analysis. The use of expert opinions is a good way to model non-linear dependencies in a simplified way, and can be used to analyze the problem under the conditions of hard-to-measure information.

Several modeling and structural analysis methods can be found in the literature, the most well-known of which are ANP (Analytic Network Process) [Saaty 1996] DEMATEL (Decision Making Trial And Evaluation Laboratory) [Gabus, Fontela 1972] and WINGS (Weighted Influence Nonlinear Gauge System) [Michnik 2013a]. While these methods use a similar algebraic mechanism, the major difference between them is the technical difficulty of using computational tools in their implementation. In the case of DEMATEL and WINGS, a typical spreadsheet is enough, whereas ANP requires specialist software. Thus, from the user's point of view, it is the DEMATEL and WINGS methods that are more convenient to use in a quick cause-and-effect analysis of the problem at hand. In both of these methods, the structural model of inter-element relationships in the system is based on a directed graph. The main difference between the methods concerns the functions described on the edges and vertices of this graph. In WINGS, in addition to the intensity and direction of the interactions (edge load), the internal force of these elements (a function described on the vertices) is considered, so that the final effect of the relationship between the elements in the system depends on the combination of these two quantities and not just one as in DEMATEL. For example, the physical process of elastic collision generates a result that is influenced not only by the velocity of the colliding bodies but also by their mass [Michnik 2013b]. In the literature, one can find several examples of the use of the above-mentioned methods for cause-and-effect analysis of the technical condition of buildings. In the first example, DEMATEL was used to determine the causes of a tank cover's failure [Dytczak et al. 2011]. The second example involved the use of a fuzzy version of DEMATEL for a cause-and-effect analysis of the pre-failure condition of the seventeenth-century Holy Trinity Collegiate Church in Olyka, Volyn oblast, Ukraine [Śladowski, Paruch 2017]. The third example uses the WINGS method in assessing the causes of the poor technical condition of the eighteenth-century wooden church of St. John the Baptist in Warszawice [Śladowski et al. 2024]. The use of the WINGS method (as an extension of the DEMATEL method) here did not factor in the impact of uncertainty in expert assessments in the analysis, which in that case was its limitation. In the present study, the use of the WINGS method addresses the shortcomings listed.

A conceptual diagram of the WINGS method algorithm is shown in Figure 1.

Using a qualitative scale, experts form an opinion on the significance (intrinsic strength) of previously identified factors of poor technical condition of the building under analysis, as well as the intensity and direction of the impacts between them. As a result, a structure of direct significance and influence between factors is formed based on these opinions. The representation of this structure is a square matrix, whose diagonal contains ratings of the significance of each factor on a four-point scale (0 – no significance, 1 – low significance, 2 – medium significance, 3 high significance). The off-diagonal ratings refer to the intensity of mutual influences / impacts between these factors (0 – no influence, 1 – low influence, 2 – medium influence, 3 – high influence). This matrix is then subjected to a calibration procedure. In the next stage, assuming a transitivity of interactions, indirect relations between factors are determined. The combination of direct and indirect relationships allows the

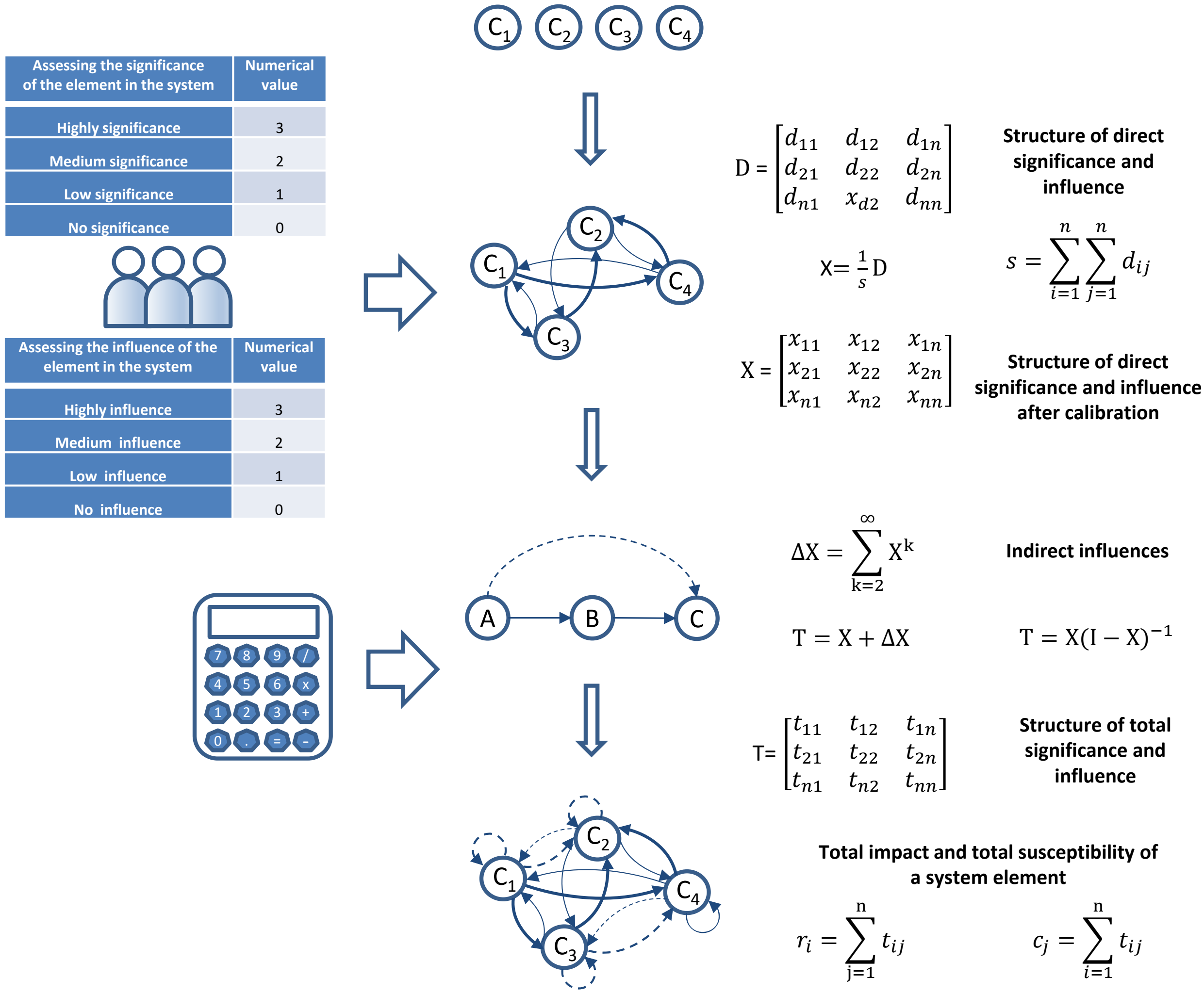

Fig. 1. Conceptual diagram of the Weighted Influence Nonlinear Gauge System (WINGS) method algorithm; original work

Ryc. 1. Schemat koncepcyjny algorytmu metody WINGS (Weighted Influence Nonlinear Gauge System); oprac. własne

mapping of a structure of the total significance and influence between factors in the system. In the last step, based on the structure of this matrix, the values of total influence of each -th factor on other factors and the total susceptibility to influences from these factors are calculated for each -th factor. The sum of values for a given factor indicates its total involvement, while the difference determines the role of this factor in the analyzed system. A positive value indicates the causal nature of factor while a negative value means that this factor is resultant. Based on the above-mentioned values, it is possible to create a so-called map of involvement and role of factors in the system (Fig. 2). It should be added that the absolute value of the difference determines the strength of the causal/resulting role of factor in the system.

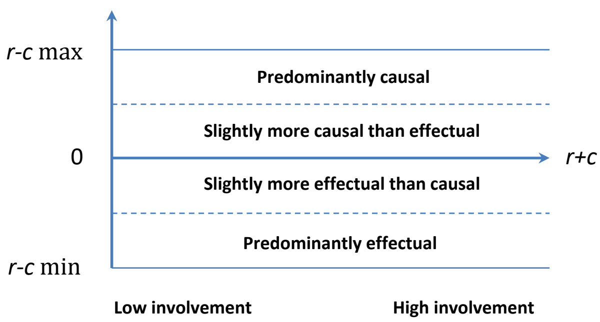

Fig. 2. Diagram of the involvement and role of elements in the system; based on: Dytczak, Ginda 2015

Ryc. 2. Schemat zaangażowania i roli elementów w systemie; na podstawie: Dytczak, Ginda 2015

Case presentation

The prisoner barracks in the BI section, with inventory numbers B-123 and B-124, were, due to their very poor technical, structural and material condition, the first buildings included in the specialized analysis conducted by a team of experts from the Cracow University of Technology. The buildings in question have floor plan dimensions of about 11.5 × 36.5 m and a base-to-ridge height of about 5.3 m. All the walls, which are only

Factor	Description
C1	High level of groundwater in the area and negative geological phenomena (presence of frost-heaving soil, a high and persistent ground- and precipitation-caused groundwater level, deformative parameters in soil layers at the footing level of the buildings)
C2	Structural faults and errors made during construction (the variety of materials used in the same group of load-bearing elements, excessively small geometric dimensions of load-bearing elements, including external masonry walls and wooden elements)
C3	Accelerated aging of the material structure resulting from the poor quality of the building materials used to construct the buildings
C4	Lack of coordinated systematic repair work over the years between 1959 and the late 1990s, which was the cause of a lot of secondary damage to the elements
C5	Errors in the solutions adopted for the repair and securing work of the main load-bearing elements over the past several decades, and especially in the initial period after the liberation of the camp
C6	Biological and microbiological corrosion of the material structure of the main supporting elements
C7	The lifetime of the buildings counted from the moment of their construction to the time of preparing contemporary securing solutions

Table 1. Factors that affected the technical condition of barracks B-123 and B-124; original work

Tab. 1. Czynniki wpływające na stan techniczny koszar B-123 i B-124; oprac. własne

12 cm thick in both longitudinal and transverse layouts, were made of solid brick, locally widened with 25 × 25 cm pilasters. The main structure of the roof cross-section is represented by a classic queen post truss with purlins and two levels of straining beams. Based on field and laboratory research, as well as an individual evaluation of the technical condition of the main load-bearing structure and its individual structural elements, the factors that influenced its technical condition were identified (Table 1). The predominant external factors constitute the set of causes of the catastrophic technical condition of the prison barracks no. B-123 and B-124 (Fig. 3a and 3b) from the 2015 expert investigation period. The main systematics of damage found in the buildings included: cracks and marks in longitudinal and gable curtain walls (Fig. 4), leaning and deformation of masonry exterior walls (Fig. 5), technical and material defects in concrete foundation walls (Fig. 6), structural degradation of concrete load-bearing elements and mortar, signs of biological and microbiological corrosion (Fig. 7), deflections of chimneys, and technical damage in finishing elements (floors, interior plaster, steel flashings, roof tiles, and window and door framing).

As a part of the proposed approach, the opinions of five experts with experience in cause-and-effect analysis of the technical condition of buildings, including listed heritage buildings, was used in this study. Using a rating scale with linguistic interpretation, each expert assessed the importance (intrinsic strength) of the factors in question, as well as the intensity and direction of interactions between them (Table 2).

Taking into account the fact of difficult-to-measure information resulting from the specificity of the problem in question, as well as its incomplete and uncertain character at the early stage of diagnosis, the authors proposed using a fuzzy extension of the WINGS method [Fedorczak-Cisak et al. 2020], which uses Triangular Fuzzy Numbers to model the

Expert 1	C1	C2	C3	C4	C5	C6	C7
C1	2	0	3	2	1	3	3
C2	0	3	3	2	3	3	3
C3	0	2	2	1	3	3	3
C4	1	1	3	3	3	3	2
C5	0	2	3	0	3	3	0
C6	0	1	3	0	1	1	3
C7	0	2	3	0	0	3	1

Table. 2. Structure of the matrix of direct significance and influence between factors as per expert opinion 1; original work

Tab. 2. Struktura macierzy istotności bezpośredniej i wpływu czynników według opinii ekspertów 1; oprac. własne

	r	c	r+c	r-c
C1	0.115	0.069	0.184	0.046
C2	0.124	0.116	0.240	0.007
C3	0.124	0.149	0.273	-0.024
C4	0.125	0.113	0.239	0.012
C5	0.114	0.123	0.238	-0.009
C6	0.113	0.132	0.245	-0.020
C7	0.104	0.108	0.212	-0.004

Table 3. Crisp values of total impact and susceptibility and their sum and difference for each factor; original work

Tab. 3. Ostre wartości całkowitego wpływu i podatności oraz ich suma i różnica dla każdego czynnika; oprac. własne

Fig. 3. Prison barrack B-123: a) general view, b) facade; photo by the authors
Ryc. 3. Barak więzienny B-123: a) widok ogólny, b) elewacja; fot. autorzy

Fig. 4. Wall damage; photo by the authors
Ryc. 4. Uszkodzenie ściany; fot. autorzy

Fig. 5. Wall deflection; photo by the authors
Ryc. 5. Ugięcie ściany; fot. autorzy

Fig. 6. B-123 concrete foundation; photo by CUT Team
Ryc. 6. Fundament betonowy B-123; fot. Zespół CUT

Fig. 7. Biological corrosion; photo by the authors
Ryc. 7. Korozja biologiczna; fot. autorzy

uncertainty of expert opinions. The authors of this article assumed a triangular shape of the membership function for the fuzzy number. This basic shape is often used in fuzzy decision models. The change in membership values between the parameters of such a function is a linear interpolation, which easily models the intuitive nature of expert opinion formulation. Due to the group nature of the opinions, the authors used a fuzzy formula to aggregate expert assessments [Pedrycz, Gomide 2007].

As a result, they obtained aggregate fuzzy number membership functions that modeled the experts' opinions on the total influence (Fig. 8) and total susceptibility (Fig. 9) of each factor in the system. The authors then used the center of gravity method [Yager, Filey 1994] to crispen the results , consequently obtaining crisp values for the total impact and susceptibility of the factors, as well as their sum and difference for each factor (Table. 3). The graphical representation of these values is the impact-relations map (IRM) (Fig. 10).

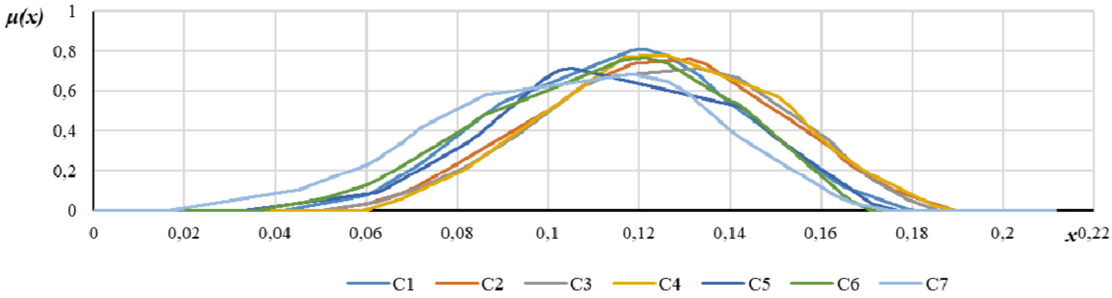

Fig. 8. Aggregate fuzzy number membership functions that model experts' opinions about the total influence of factor on the other factors in the system; original work

Ryc. 8. Agregowane funkcje przynależności liczb rozmytych modelujące opinie ekspertów na temat całkowitego wpływu czynnika na pozostałe czynniki w systemie; oprac. własne

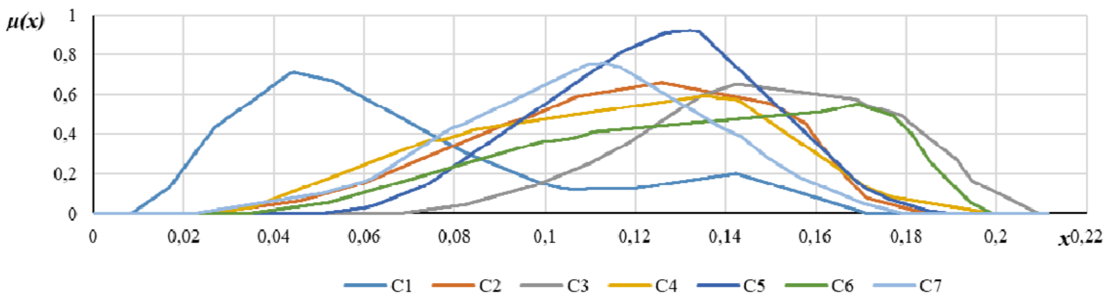

Fig. 9. Aggregate fuzzy number membership functions that model experts' opinions about the total susceptibility of factor to the influence of other factors in the system; original work

Ryc. 9. Zagregowane funkcje przynależności liczb rozmytych modelujące opinie ekspertów na temat całkowitej podatności czynnika na wpływ innych czynników w systemie; oprac. własne

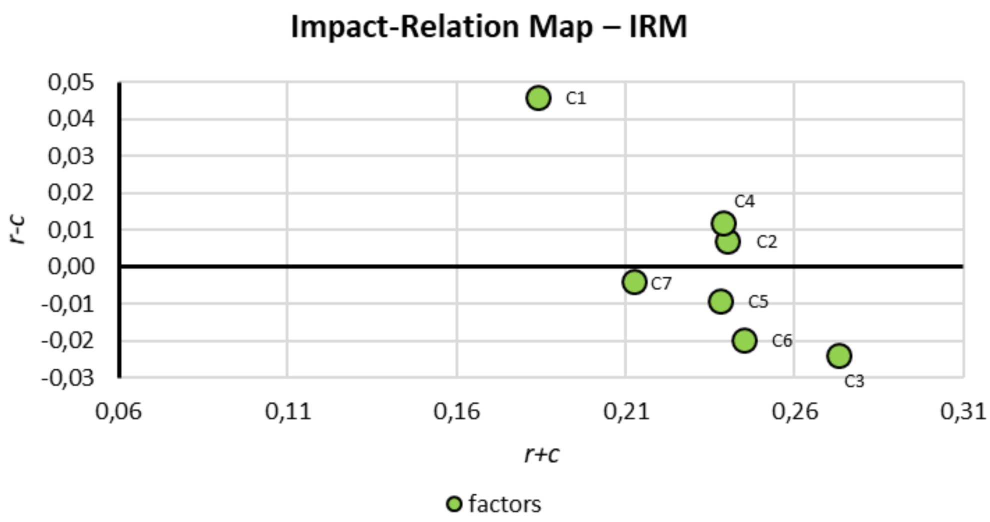

Fig. 10. Impact-relations map for factors; original work

Ryc. 10. Mapa relacji wpływu dla czynników; oprac. własne

The factor involvement ranking for determining the causes of the poor technical condition of a historic building is determined by the value of the indicator (the higher the value of this indicator, the higher the rank of the factor).

Analysis of results

The impact-relations map obtained shows that factor C1, associated with unfavorable soil and groundwater conditions, had a clearly dominant causal nature. A slightly smaller causal role with a higher involvement than factor C1 was observed for factors C4 and C2, associated with errors in the original construction of the buildings and the absence of systematic renovation during operation, respectively. Factor C5 (faulty solutions as part of the renovation work) is characterized by greater susceptibility to influence from other factors compared to its role of influence in the system. Similarly, factor C6 (corrosion of the material structure of the main load-bearing elements) clearly plays the role of an effect rather than a cause of the poor technical condition of the buildings. Factor C3 (accelerated aging of the structure made of low-quality materials) has the highest involvement index but a negative role index in the system, indicating that it is the most susceptible factor among those considered. In contrast, the role played by factor C7 (the buildings' age) can be considered neutral, with low involvement in the system.

The synthetic results obtained using the FWINGS method align with the conclusions of the groundbreaking research and analysis carried out by the team from the Cracow University of Technology, which consequently identified methods for securing and strengthening individual elements and the entire support structure of prisoner barracks no. B-123 and B-124. The pilot implementation under the Global Conservation Plan for the Auschwitz-Birkenau Museum and Memorial completed with the opening of masonry barracks B-123 and B-124 to the public resolved the key problems of wall deformation and eliminated hazards that arose from defects in foundation elements and adverse water and soil conditions [Karczmarczyk et al. 2016, Bartyzel et al. 2019]. The share, character and intensity of the indicated factors, from C1 to C7, are a full reflection of the actual state of affairs before the renovation and restoration work. The above conclusions provide evidence of the high application potential of the approach presented in this article.

Conclusions

The purpose of this article was to propose the FWINGS (Fuzzy Weighted Influence Nonlinear Gauge System) method for analyzing the cause-and-effect relationships between factors of poor technical condition of buildings. The method's operation has been presented using the case of the prisoner barracks with inventory number B-123 and B-124, located in section BI of the former Auschwitz-Birkenau concentration and death camp in Oświęcim. The alignment of the results obtained using the FWINGS method with the results of the detailed investigation demonstrates the method's high potential for application. It is a qualitative method, which is why it can be used under conditions of access to often uncertain, incomplete and imprecise information (at an early investigation stage) about a building, and accounts for the subjective expert opinions, as the uncertainty and subjectivity of expert opinions is partially counteracted by fuzzy logic elements.

The approach presented, based on the FWINGS method, can be used for a preliminary (at a stage where precise findings are yet to appear), estimative and—most importantly—quick expert assessment of the impact of various factors on a building's technical condition. This is of special significance in situations where a given building requires the immediate securing and rescue measures before detailed target investigation may commence and comprehensive conservation work can begin. However, this approach has limitations, namely the need to identify potential factors that contribute to the poor technical condition of the building to be analyzed. In the future, it is advisable to continue the practical verification of the method using other buildings as cases.

Footnotes / Przypisy

[1] Co-author of this article is also: Anna Porębska, orcid.org/0000-0001-7939-9947, Ph.D. Eng. Arch., Cracow University of Technology, Faculty of Architecture.

[1] Współautorem artykułu jest również: Anna Porębska, orcid.org/0000-0001-7939-9947, dr inż. arch., Politechnika Krakowska, Wydział Architektury

References / Bibliografia

Secondary sources / Opracowania

Bartyzel Bogusław et al., *Zachować autentyzm: Konserwacja baraków murowanych dawnego Kl Auschwitz II-Birkenau*, Oświęcim 2019.

Celadyn Wacław, Porębska Anna, Paruch Roman, Karczmarczyk Stanisław, *Methods for protecting, conserving, repairing and reinforcing highly vulnerable world heritage sites: Guidelines for the sector BI of the former KL Auschwitz II-Birkenau Master Plan for Preservation*,"Wiadomości Konserwatorskie" 2021, No. 68S.

Dytczak Marek, Ginda Grzegorz, *Miejsce metody DEMATEL w rozwiązywaniu złożonych zadań decyzyjnych*, "WSB University in Wroclaw Research Journal" 2015, vol. 15, iss. 5.

Dytczak Marek, Ginda Grzegorz, Wojtkiewicz Tomasz, *Analiza związków przyczynowo-skutkowych w awarii konstrukcji przy użyciu metody DEMATEL,* Application of DEMATEL for identification of cause-effect relations in the case of failure analysis 2, 24–27, 2011.

Gabus Andre, Fontela Emilio, *World Problems an Invitation to Further Thought within the Framework of DEMATEL*, Geneva 1972.

Fedorczak-Cisak Małgorzata, Kowalska-Koczwara Alicja, Pachla Filip, Radziszewska-Zielina Elżbieta, Szewczyk Bartłomiej, Śladowski Grzegorz, Tatara Tadeusz, *Fuzzy Model for Selecting a Form of Use Alternative for a Historic Building to be Subjected to Adaptive Reuse*, "Energies" 2020, vol. 13, iss. 11.

Kańka Stanisław, Stryszewska Teresa, Tracz Tomasz, Karczmarczyk Stanisław, Paruch Roman, *Methods oftesting and assessing the technical condition of chosen building structures located in the area of the Auschwitz--Birkenau State Museum in Oświęcim*, "Civil and Environmental Engineering Reports" 2–15, vol. 19, No. 4.

Karczmarczyk Stanisław, Paruch Roman, Kańka Stanisław, Tracz Tomasz, *Badania nieniszczące i wzmacnianie zabytkowych drewnianych więźb dachowych*, "Materiały Budowlane" 2016, vol. 6, No. 526.

Łopuska Anna, Autentyzm versus udostępnienie, *Granice kompromisów w konserwacji byłego obozu Auschwitz-Birkenau*, "Ochrona dziedzicwa kulturowego" 2017, No. 3, 2017.

Michnik Jerzy, *Weighted Influence Non-linear Gauge System (WINGS)–An analysis method for the systems of interrelated component*, "European Journal of Operational Research" 2013, vol. 228, iss. 3.

Michnik Jerzy, *Wielokryterialne metody wspomagania decyzji w procesie innowacji,* Katowice 2013.

Paruch Roman, Porębska Anna, Beyond Standards: Framework for Monitoring, Protection, and Conservation of Highly Vulnerable Cultural Heritage Sites in the Context of Anthropopressure and Climate Change, "Sustainability" 2026, vol. 18 (1).

Pedrycz Witold, Gomide Fernando, *Fuzzy systems engineering: Toward human-centric computing*, Hoboken 2007.

Saaty Thomas L., *Decision Making with Dependence and Feedback: The Analytic Network Process*, Pittsburgh 1996.

Śladowski Grzegorz, Drozd Wojciech, Paruch Roman, *Wstępna ocena przyczyn złego stanu technicznego zabytkowego budynku drewnianego z wykorzystaniem modelowania i analizy strukturalnej*, "Przegląd Budowlany" 2024, vol. 95, No. 6.

Śladowski Grzegorz, Paruch Roman, *Expert cause and effect analysis of the failure of historical structures taking into account factors that are difficult to measure*, "Archives of Civil Engineering" 2017, vol. 63, No. 2.

Yager Ronald, Filev Dimitar, *Essentials of fuzzy modeling and control*, New York 1994.

Abstract

This paper proposes a systems-based approach to the preliminary analysis of poor technical condition factors in historic buildings using the FWINGS method (Fuzzy Weighted Influence Nonlinear Gauge System). The approach's application potential is presented on the example of prison barracks of the former Auschwitz-Birkenau concentration camp in Oświęcim. The results were verified by comparison with the findings of an expert report prepared by a Cracow University of Technology team, based on which a successful project involving conservation and securing works was completed. The alignment of the results shows the approach's application potential. Understanding the cause-and-effect relationships that the approach enables, and identifying interdependencies between the factors of poor technical condition in heritage buildings, provides effective support in decision-making processes and is useful for effective monitoring of the condition of world heritage areas.

Streszczenie

W artykule przedstawiono systemowe podejście do wstępnej analizy czynników wpływających na ocenę złego stanu technicznego obiektów zabytkowych z wykorzystaniem metody FWINGS (Fuzzy Weighted Influence Nonlinear Gauge System). Możliwości jej zastosowania zaprezentowano na przykładzie baraków więźniarskich byłego niemieckiego obozu koncentracyjnego i zagłady Auschwitz-Birkenau w Oświęcimiu. Uzyskane wyniki zweryfikowano przez porównanie z wnioskami z opracowanej przez zespół Politechniki Krakowskiej ekspertyzy, która stanowiła podstawę realizacji zakończonego sukcesem projektu prac konserwatorskich i zabezpieczających. Zbieżność wyników potwierdza potencjał zaproponowanego podejścia. Zrozumienie związków przyczynowo--skutkowych dzięki zastosowaniu zaproponowanej metody, w tym identyfikacja współzależności między czynnikami złego stanu technicznego obiektów zabytkowych, może zapewnić efektywne wsparcie procesów decyzyjnych i być przydatne w monitorowaniu stanu obszarów światowego dziedzictwa.