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Research paper

The application of fuzzy set theory in the risk assessment during the construction

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Abstract: Traditional risk modeling techniques, such as statistical and probabilistic methods, which form the basis of risk estimation and analysis, are not always economically or socially effective tools in construction. This is due, among other things, to the discrepancy between the planning period of a project and its implementation and sustainability. Static or dynamic methods of measuring the effectiveness of projects are commonly used, as well as operational methods to solve problems in specific decision-making situations. The inclusion of subjectivity and the lack of complete and precise information severely limits, and sometimes even prevents the use of traditional methods. Applying fuzzy set theory to model complex issues such as risk seems a desirable and justifiable measure in such a case. The application of fuzzy sets in construction is not a new issue. However, most research studies on the use of fuzzy systems in the construction industry have proved to be either too simplistic or too detailed, therefore fuzzy risk assessment matrices have been proposed. The proposed alternative risk assessment methods are based on fuzzy set theory while considering standard recommendations. The paper discusses basic information on design strategies for building structures taking into account standard recommendations for modeling and risk assessment in construction. An example illustrating the application of the proposed qualitative and quantitative risk estimation methodology to a bridge structure is also included.

Keywords: risk assessment, fuzzy matrix, fuzzy systems, civil engineering structures, bridges

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1. Introduction

The nature and peculiarities of the construction industry mean that, despite the considerable difficulty of quantification, the analysis of the impact of risk factors on a construction project continues to be an issue addressed not only in academic research, but also in practice. To the risk modeling uses economic, statistical, and financial techniques to predict potential/maximum risk [1, 2]. Some researches break modeling into three main types: quantitative, qualitative, and a hybrid version. Quantitative modeling relies on statistical data [3, 4], probabilistic modelling [5] and numerical simulations [6], while qualitative relies more on expertise and potentially subjective knowledge [7] and a combination of the two is where the hybrid model comes in [8–11]. The use of traditional estimation risk estimation techniques such as statistical and probabilistic methods, which form the basis of risk estimation and analysis, are not always economically or socially effective tools in the construction industry.

Construction projects, like any business venture, involve uncertainty in the achievement of the anticipated outcome. This is primarily due to the discrepancy between the planning of the project and its implementation and durability.

Uncertainty affects not only the definition of objectives and criteria, but above all the indicators for their evaluation. Static or dynamic methods of measuring the effectiveness of ventures are commonly used, as well as operational methods that allow solving problems in specific decision-making situations, e.g. changes in market conditions, unpredictable environmental phenomena. Hence, the construction entrepreneur, already at the planning stage, must take a number of measures to safeguard against possible risks arising from uncertainties that may prevent the planned implementation of the project. Taking into account subjectivity and the lack of complete and precise information severely limits and sometimes even prevents the use of traditional methods. In such a case, the use of fuzzy set theory to model complex issues of risk seems a desirable and justifiable measure.

The application of fuzzy sets in the construction domain is not a new issue [12–17]. However, as the literature indicates. the first studies on the use of fuzzy logic in this industry proved to be either too simplistic or too detailed [8–22]. This paper discusses basic information on design strategies for building structures taking into account standard recommendations for modeling and risk assessment in the construction process discussed in [18, 19, 22–26]. Alternative risk assessment models based on fuzzy set theory, taking into account standard recommendations [27–30] and an example illustrating the application of the proposed risk estimation methodology are presented.

2. Design strategies

The standard EN 1991-1-7 [27] distinguishes two basic strategies for designing structures for accidental actions. The first one is based on designing structures for accidental actions with values determined by statistical tests or with contractual values. These strategies are based on designing structures for accidental actions as well as designing structures for sufficient minimum resistance or preventing the occurrence or reducing the values of accidental actions. The second approach is strategies based on limiting the extent of local damage when accidental actions are indeterminate and characterized by very high variability or difficult to assess frequency of occurrence. These design strategies involve stiffening the structure, designing key elements for accidental impacts of normative value and meeting the normative recommendations specified in the relevant norms [21, 31]. Most structural design codes presently in place, such as the Eurocodes [27, 31] defined classes of consequences for design of possible structural failure and establish consequence classes (CCs) for that purpose. EN 1990 [32] distinguishes three CCs depending on the type and use of the structure (buildings, civil works). The example given in the code for CC1 structures, in which the consequences in terms of number of lives lost are deemed to be scant or nil, is agricultural buildings where people are seldom present. Residential and office areas are listed as typical examples of the medium class or CC2 buildings, whilst those where people may congregate, such as grand stands or concert halls, are classified as CC3 (where many human lives may be lost in the event of collapse). Bridge structures are generally in consequence class CC2 or CC3 according to EN 1990 [32]. The Annex E of the EN 1990 [32] gives informative guidance for enhancing the robustness of buildings and bridges. It provides strategies based on limiting the extent of damage, while the explicit design of structures for identified accidental action is covered within the scope of EN 1991 [33]. This design strategy is frequently adopted for structures possessing a limited level of redundancy such as tensile structures, 2D and 3D trussed systems, cable stayed and suspension structures [34]. Key elements can also be used in addition to other design features to improve the robustness of high-risk constructions [35]. Furthermore, this design approach is often the only rational approach when retrofitting existing constructions. Depending on the context, examples of potential key elements could be columns, load-bearing walls of a building, piers of continuous bridges or cables in a cable-supported structure [36]. The Annex A of EN 1991-1-7 [2] further details the application of such strategies to the different building categories. More stringent requirements are recommended going from CC1 to CC3, reflecting the increased level of risk due to structural collapse. Both EN 1993 [37] and EN 1994 [38] provide recommendations which may be either directly or indirectly relevant to the design and detailing for robustness, including information related to the ductility and rotation capacity of beams and partial-strength joints, amongst others.

According to [18, 21], the strategies recommended for the design of constructions of consequence classes 1 and 2 are normative and have been used in practice for many years. In turn, it was concluded in [18, 21, 31] that normative guidelines for risk analysis and assessment, especially quantitative risk analysis and assessment, are still quite general and their application in construction practice requires specialized knowledge, which is often based on difficult to access, incomplete and imprecise data.

2.1. Risk analysis

Risk is a concept appearing in several disciplines, but all definitions can be represented by three components: first, one or several potential hazards; second, the probability of those hazards going active (often called exposure); and third, the probable counter-effect experienced when the hazard occurs.

Currently, legal acts and technical standards contain definitions of basic concepts related to risk analysis and assessment. However, the definition of risk proposed in [28] is general and the mathematical formula for estimating risk is too complicated and not very practical in engineering applications. In [27, 28] the terms risk and risk analysis are defined as follows:

- Risk (EN 1991-1-7, 2008) [27] – A measure of the combination (usually the product) of the probability or frequency of occurrence of a defined hazard and the magnitude of the consequences of the occurrence.
- Risk analysis (EN 1991-1-7, 2008) [27] – A systematic approach for describing and/or calculating risk. Risk analysis involves the identification of undesired events, and the causes and consequences of these events.

In practice, the concept of risk is combined with, among others, with the following issues:

- Consequence (EN 1991-1-7, 2008) [27] – A possible result of an event. Consequences may be expressed verbally or numerically in terms of loss of life, injury, economic loss, environmental damage, disruption to users and the public, etc. Both immediate consequences and those that arise after a certain time has elapsed are to be included.
- Hazard (EN 1990, 2002) [32] – An unusual and severe event, e.g., an abnormal action or environmental influence, insufficient strength or resistance, or excessive deviation from intended dimensions.
- Hazard Scenario (EN 1991-1-7, 2008) [27] – A critical situation at a particular time consisting of a leading hazard together with one or more accompanying conditions which leads to an unwanted event (e.g., complete collapse of the structure).
- Risk assessment [39] – A process of risk analysis and risk evaluation (with risk evaluation containing risk acceptance and option analysis).
- Vulnerability [36] – Susceptibility of a structure to suffer initial damage when affected by abnormal events. A structure is vulnerable if abnormal events easily lead to initial damage.

Risk is normally compared by the size of the relevant loss [40]. The basic difference between risk and uncertainty is based on how much a series of the outcomes of potential decisions and the probability of their occurrence is quantifiable. Uncertainty often refers to the fact that decision making is not easy to be quantified and may be related both to decision outcomes and the probability of their occurrence. Uncertainty may also be related to decision makers preferences [40, 41]. Quantifiability is the key feature of risk, but the relationship between the definition and measurement of risk is not linear. In reality, the process of identifying risk reflects a decision moment, which depends on the decision maker's attitude, the production process used as the basis and the characteristic features of the decision problem. Those factors affect the two-step process of defining risk; in the first step, you must define which consequences or outcome dimensions are included; the next step is the construction of risk indicators based on the consequences selected in phase one [40].

In the case of construction, threats are commonly associated with uncertainty. Uncertainty is the result of a lack of complete, reliable information about the influence of external and internal factors with regard to the implementation and subsequent use of a construction work. It can therefore be assumed that uncertainty is a function of time and information. Risk, on the other hand, is a function of that part of uncertainty for which the probability of the contemplated event can be determined. Risk comprises positive and negative dimensions.

Positive risks include events that can be equated with emerging opportunities that can bring tangible benefits. Negative risks, on the other hand, refer to risks that can bring losses. Consequently, it is the negative dimension of risk that requires attention in the theory and practice of risk management during the implementation and use of construction works.

In mathematical terms, risk is a measure of hazard defined as the Cartesian product of the probability and consequence of a hazardous or undesirable event that may occur during the construction or use of a construction facility [19, 21, 22, 24–26, 42]. In the case of the random nature of hazards E_i, treated as random events, the risk can be calculated according to Equation 2.1 and considered as a determined or random quantity [21, 43]:

$$R = \sum_{i=1}^{n} p_f(E_i) \cdot C_i \tag{2.1}$$

where: $p_f(E_i)$ – probability of a hazard occurring, being a random event, C_i – losses associated with the consequences of this event, usually financial.

This approach to risk analysis was used in [1, 44, 45]. However, based on the literature analysed, one can also encounter a definition of risk in line with probability theory, and more precisely with the so-called second phase of risk analysis that is estimation of probability. In these studies, risk analysis is equated with the probability of an adverse event occurring. Such a definition of risk in construction was used in [46, 47].

Nowadays, risk management is considered a key part of construction project management, which is why large companies create their own professional teams or departments for risk management. According to [48], risk analysis and assessment is a fundamental element of construction project management and is related to reducing uncertainty over time. Commonly used risk assessment tools and techniques in the construction industry include ETA – Event Tree Analysis, Monte Carlo Analysis, FMEA – Failure Mode and Effect Analysis, PERT-Program Evaluation and Review Technique [19].

However, all these approaches require high quality data obtained from previous projects [48, 49]. Such data are unfortunately very often difficult to access. Thus, risk analysis is a complex subject full of uncertainty, and risk assessment can be influenced by a number of factors, e.g. factors related to economics and political considerations, which are not well defined and difficult to quantify [49]. Consequently, using traditional mathematical tools, it is very difficult to incorporate incomplete and subjective information in risk analysis and assessment. As research indicates, fuzzy sets and fuzzy logic are powerful tools for dealing with imprecise and incomplete information and subjectivity. However, these methods are still not sufficiently developed and widely used in construction [19, 49].

Two methods can be used for the risk analysis of buildings and structures according to [27]:

- a qualitative analysis consisting of the identification of hazards and their corresponding impact scenarios and the basic use of the structure in order to demonstrate that their safety consequences are acceptable; many methods have been developed to support risk analysis, including Hazard and Operability Study (HAZOP) and Process Hazard Analysis (PHA), fault tree analysis, event trees, causal networks, etc., which can also be applied to building structures,

– a quantitative analysis based on risk estimation using Equation 2.2 is also recommended in [28]:

$$R = \sum_{i=1}^{n_H} p(E_i) \sum_{j=1}^{n_p} \sum_{k=1}^{n_s} p(D_j/E_i) p(S_k/D_j) C(S_k) \tag{2.2}$$

where the structure is assumed to be subjected to n_H different hazards that can damage it in n_p different ways, where the behaviour of the damaged structure can be considered in the number n_s of adverse S_k states causing consequences $C(S_k)$, $p(E_i)$ is the probability of the i-th hazard, $p(D_j/E_i)$ is the conditional probability of the j-th damage state causing the i-th hazard, and $p(S_k/D_j)$ is the conditional probability of the k-th adverse behaviour of the structure S_k causing the j-th damage state.

The most common quantitative risk analysis includes:
– estimating the probability of consequences of possible hazards of a fixed intensity,
– estimating the probability of various failures and their consequences for the considered hazards,
– estimating the probability of adverse reactions to local structural damage and the associated consequences [21].

Most often, the causes of failures are factors not considered during the design and condition assessment phase. In such a situation, systematic risk analysis and assessment is recommended as the most appropriate and promising method to ensure a satisfactory level of resilience of the structure to exceptional impacts, including structural safety.

2.2. Identification of hazards

Identifying hazards and establishing possible scenarios for catastrophes or failures of building structures and assessing the probability of their occurrence and consequences are among the basic tasks involved in the risk analysis of construction projects. The risks associated with the different stages of the construction process vary and depend on the hazards associated with each stage. Two types of hazards can be distinguished by their causes: natural and anthropogenic. Natural hazards are related to the random nature of the impacts on construction objects, the random properties of the materials and the geometric dimensions of the elements from which they are made. Anthropogenic hazards are related to the human factor and are directly linked to the construction process. They mainly arise from unintentional or intentional deviations from the principles and rules of the construction art (human errors and negligence).

According to [18, 21, 31], hazards in construction can be divided into three categories: predictable, unrecognized/ignored and unpredictable. The individual categories of hazards include:
– predictable;
– standard such as dead weight, imposed loads, climatic, exceptional and natural loads, including hurricanes, landslides, floods;
– exceptional caused by human activities unrelated to the structure under consideration: fires, internal explosions, impacts of trucks;
– caused by human errors committed in the process of design, execution and maintenance;

– caused by deliberate, destructive human actions, including acts of terrorism.
– unrecognized/ignored:
– structural or material defects that are present but not detected during inspections or tests due to inadequate quality control procedures;
– gradual deterioration of construction materials that is ignored or underestimated by property managers or maintenance teams, e.g., steel corrosion, concrete degradation;
– changes in the use of a structure leading to overloads not anticipated in the original structural design;
– non-compliance with maintenance or technical inspection recommendations, which can lead to undetected defects.
– unpredictable:
– natural disasters of extreme strength or type that could not be predicted based on available historical data, e.g., earthquakes of a magnitude greater than any recorded in the location, unexpected volcanic eruptions;
– terrorist attacks using new or unconventional methods that are difficult to predict and counteract at the design stage;
– failure of critical external infrastructure, e.g., collapse of the power grid or water supply system, which could not have been predicted and directly affects the safety of the structure;
– sudden events caused by human errors that are difficult to predict, e.g., mistakes in the operation of construction machinery leading to accidents.

2.3. Risk acceptance criteria

Proposals for criteria in the form of mainly qualitative and mixed matrices of acceptable risk levels have been presented in many publications, including [21, 31, 44, 45]. Still, the fundamental issue is to establish the risk acceptance criterion. The standard [27] presents a mixed criterion in tabular form (see Table 1).

Table 1. A matrix of acceptable risk levels made based on the EN 1991-1-7 [27]

Consequences **Probability of failure**	**Very low**	**Low**	**Medium**	**High**	**Very high**
> 10–1	X				
10–2	X				
10–3		X			
10–4			X		
10′–5				X	

Legend: X – the highest acceptable level of risk

Quantitative risk acceptance criteria are often presented in the form of graphs of the relationship between the acceptable probability of failure and the expected number of fatalities, the so-called N-F curves described in ISO 13824 [28] – see Fig. 1.

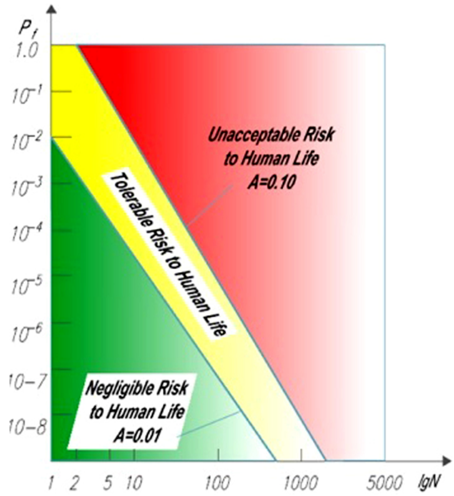


Fig. 1. N-F diagram according to made based on ISO 13824 [28]

Risk matrixes and similar tables are widely used in the less detailed semi-quantitative or qualitative risk analyses. A risk matrix is based on the same principle as a FN-curve expressing risk as a combination of frequencies or probabilities and consequences. But unlike FN-curves the risk matrix use intervals of probabilities and categories of consequences. A risk matrix does not pretend to express the exact level of risk, but is useful to highlight the different contributions to risk from the underlying hazards. Risk matrixes (Table 2) and similar tables may be feasible tools in risk meetings aiming at identifying and evaluating hazards in a direct manner [28].

Table 2. Matrix of acceptable risk levels according to ISO 13824 [28]

Consequence **Probability of failure**	**Minor injuries**	**Severe injuries**	**Fatalities**
Very high (at least once a year)	yellow	red	red
High (once in 2–9 years)	yellow	red	red
Low (once in 10–50 years)	green	yellow	red
Very low (less than every 50 year)	green	yellow	yellow

Legend:

green	Risk mitigation measures not necessary
yellow	Risk mitigation measures should be considered (ALARP)
red	Risk mitigation measures necessary

An example of a matrix for a mixed risk acceptability criterion is the diagram developed by S. Wolinski – see Fig. 2 [31].

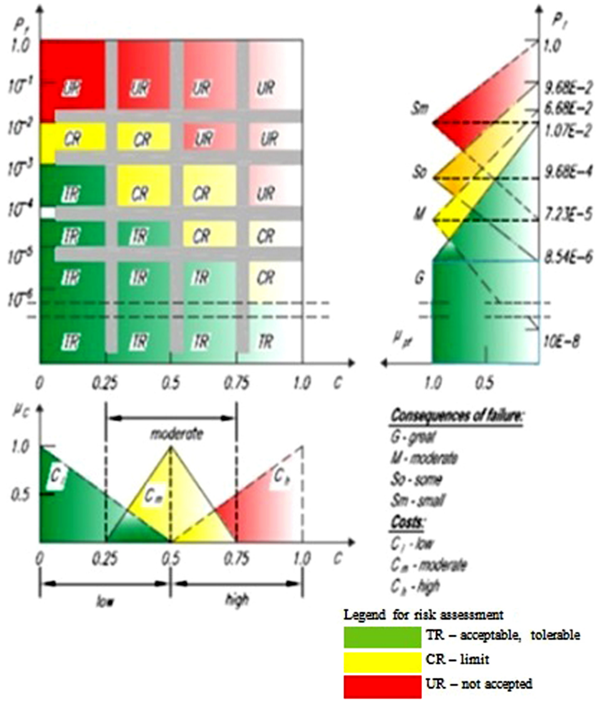


Fig. 2. Matrix of the mixed risk acceptability criterion made based on S. Wolinski's proposal [31]

3. Proposal of risk matrix

According to [31, 50], the application of fuzzy set theory can effectively reduce the complexity of ill-defined problems, it can also enable the use of imprecise and subjective information, improve the cognition of construction expert systems, enable the modelling of uncertainty, and can prove to be an effective tool in conflict resolution in construction. Clearly, the most reliable results can be obtained by combining fuzzy set theory with the risk assessment process to minimise uncertainty and uncertain information. Fuzzy inference systems are systems with knowledge bases – knowledge-based systems, where a linguistic approach is used during modelling. Fuzzy decision function and fuzzy inference are techniques widely proposed for decision-making and modelling. A fuzzy decision function is a tool that combines decision goals and constraints in identifying a decision-maker's preferences [51, 52]. Fuzzy inference introduces transparency by defining a rule database. A risk assessment model based on fuzzy inference techniques can be represented schematically as shown in Figure 3.

The model presented in Fig. 3 includes the following elements:

– Database: The foundation of the model, where all relevant data concerning potential risks, historical incidents, expert judgments, and other related information is collected and organized. This data serves as the primary input for identifying and evaluating risk criteria.

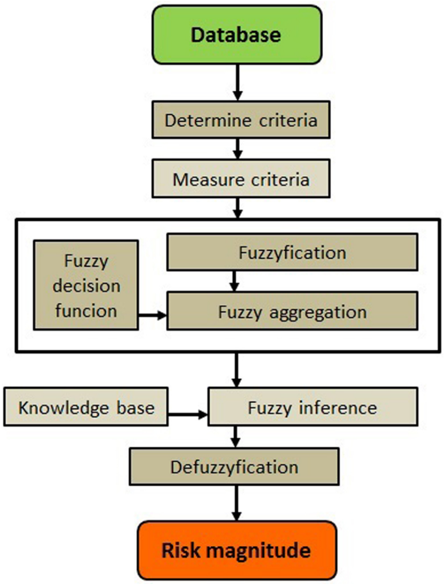


Fig. 3. Risk assessment model made based on [19]

- Determine Criteria: This step involves defining the specific criteria that will be used to assess risks within the construction project. Criteria could include factors such as the probability of risk occurrences, the severity of potential impacts, and the vulnerability of the construction project to these risks.
- Measure Criteria: Once the criteria are established, they are then measured or evaluated. This evaluation could be based on quantitative data, such as statistical analyses, or qualitative assessments, such as expert opinions.
- Fuzzification: The measured criteria are transformed into fuzzy values using linguistic variables (e.g., low, medium, high) instead of precise numerical values. This process allows the model to handle the inherent uncertainty and imprecision in the assessment of construction risks.
- Fuzzy Decision Function: Fuzzy Aggregation: At this stage, a fuzzy decision function aggregates the fuzzified criteria to generate an overall assessment of risk. This involves applying fuzzy logic operators to combine the input criteria according to predefined rules, reflecting the complex interrelations between different risk factors.
- Knowledge Base: Fuzzy Inference: The knowledge base consists of a set of fuzzy logic rules derived from expert knowledge or empirical data. Fuzzy inference uses these rules to interpret and process the aggregated fuzzy data, producing a fuzzy output that represents the assessed risk level.
- Defuzzification: This step converts the fuzzy output from the inference process into a crisp, numerical value or category that represents the magnitude of risk. Defuzzification is crucial for making the results interpretable and actionable, providing a clear indication of the risk level.

– Risk Magnitude: The final output is the risk magnitude, a quantifiable measure or classification of the risk based on the defuzzified value. This magnitude can then be used to make informed decisions regarding risk mitigation, management strategies, or other necessary actions to address the identified risks.

This process allows for a nuanced and flexible approach to risk assessment in construction projects, accommodating the complexity and uncertainty inherent in such endeavors.

In order to carry out the risk analysis following the standard recommendations for risk levels defined in the standard [27] and the literature [19, 21, 44, 45], a mixed risk matrix was developed. In the adopted model, the input values are the probability of failure (P_f) and the consequences of failure (C), which were adopted as the two basic criteria for assessing the risk magnitude.

The risk value was presented as a five-element set whose elements are fuzzy subsets described by linguistic variables: $R = \{\text{very low, low, medium, high, very high}\}$. These variables are described by linear and triangular type membership functions. The input variables, i.e. the probability of failure (P_f) and the consequences of failure (C), were described in an analogous way. The probability of destruction/failure largely depends on experience and historical data obtained from company records and records of construction disasters and failures. The fuzzy functions and linguistic variables of the probability of destruction can be described according to the abovementioned documents [19, 21, 27, 44, 45] as shown in Table 3.

Table 3. Defined variables for the input variable "probability of destruction"

Type of fuzzy function	**Linguistic type variable**	**Interpretation**	**Probability of failure according to EN 1991-1-7 [27]**
Linear	VH – very high	Occurrence almost inevitable	$> 10^{-1}$
Triangular	H – high	Frequently occurring	$10^{-1} - 10^{-2}$
Triangular	M – medium	Occasionally occurring	$10^{-2} - 10^{-3}$
Triangular	L – low	Likely to happen once in the project/object life cycle	$10^{-3} - 10^{-4}$
Linear	VL – very low	Occurrence unlikely	$< 10^{-5}$

The term Consequences denotes the degree and scale of the impact of the destruction if the risk occurs. Consequences can be assessed in terms of their impact on time, cost, quality, environment, health and safety. Table 4 provides a description for the input variable – consequences in relation to the risk of project delay/damage to a building.

A general interpretation of the linguistic risk variables is given in Table 5.

The elaborated risk matrix (Table 6) is the result of calculations according to formula (2.2). The knowledge base, on the other hand, comprises the inference process for which the fuzzy inference process is based on "if-then" rules. In this case, the rule database is formed by 25 rules (Table 6), where VH, H, L and VL represent very high, high, medium, low and very low risk levels, respectively.

Table 4. Defined variables for the input variable "consequences"

Type of fuzzy function	**Linguistic type variable**	**Interpretation**
Linear	VH – very high	Construction object failure/building disaster
Triangular	H – high	Significant delay in execution and serious damage to the structure
Triangular	M – medium	Delays occur, intermediate structural damage
Triangular	L – low	Minor delays and minor structural damage
Linear	VL – very low	No delays or damage to structures

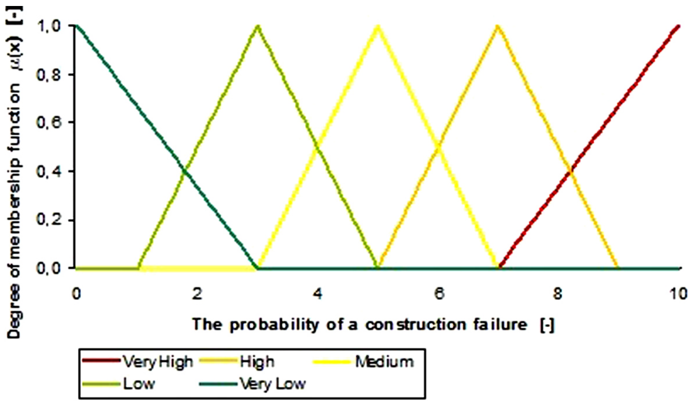
Table 5. Defined variables for the output variable "risk"

Type of fuzzy function	**Linguistic type variable**	**Interpretation**
Linear	VH – very high	Unacceptable risk, the identification of specific actions required
Triangular	H – high	Relevant. Risk assessment and definition of actions required
Triangular	M – medium	Medium level. Risk management required
Triangular	L – low	Tolerable risk
Linear	VL – very low	Irrelevant risk

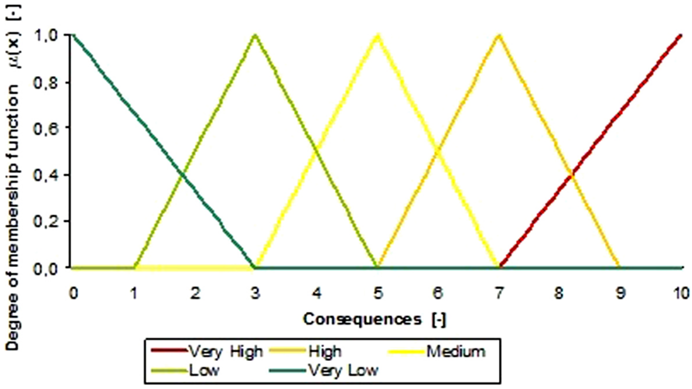
Table 6. Qualitative risk matrix

Risk		**Consequences of failure – *C***				
		VL	**L**	**M**	**H**	**VH**
Probability of failure – P_f	VH	L	M	H	H	VH
	H	L	M	H	H	H
	M	L	L	M	H	H
	L	VL	L	L	M	M
	VL	VL	LV	L	L	L

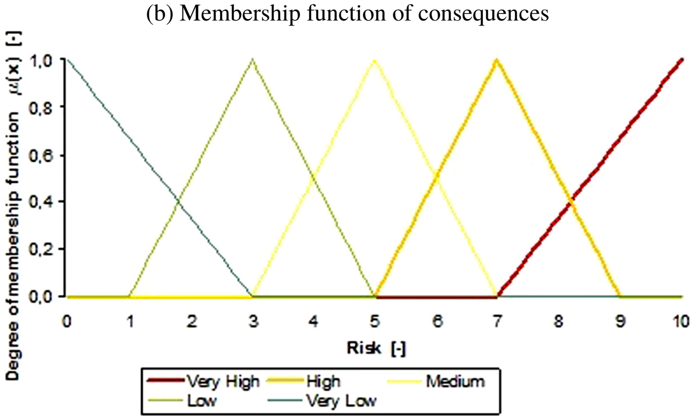
Probability of destruction (P_f) and consequences (C) are the criteria for risk assessment. The risk itself is described according to Tables 3– 6 as linear and triangular membership functions, which are defined as proposed in [8] – see Figure 4.



(a) Membership function of the probability of a construction failure



(b) Membership function of consequences



(c) Membership function of risk

Fig. 4. (a) Membership function of the probability of a construction failure, (b) membership function of consequences, (c) membership function of risk

4. Calculation example for risk estimation

A risk quantification was carried out for the foundation failure of a flyover for which foundation work had not been carried out properly.

4.1. Description of the studied object

The structure under consideration was designed as a monolithic, six-span structure with a beam and plate cross-section. The cross-section of the superstructure is formed by a monolithic system of deck slab and beams, with the left-hand carriageway designed as a three-beam system and the right-hand carriageway as a two-beam system of prestressed concrete with a reinforced concrete deck slab. Above the outermost supports, cross-beams extended under the bridge slab supports were designed. Above the intermediate supports, monolithic cross-beams only occur between the main beams. The height of the superstructure beams is 1.30 m. The deck slab between the beams is 0.30 m thick, increased locally to 0.45 m when fixed in the girders. On both sides of the structure, the podium cantilevers of the deck slab are designed with an overhang of approximately 2.60 m. The deck slab along the length of the cantilevers has a variable thickness of 0.20 m to 0.45 m. The superstructure is spanned over hinged and pinned supports. The view of the considered object is shown in Fig. 5.

Fig. 5. General view from below of the built superstructure of the left-hand carriageway and the pillars

The bridge abutments were designed and executed as solid walls, with wings in the form of standing side walls on the embankment side, placed on the continuous footings. The sidewalls are dilated from the abutment body from one side, while from the other side the sidewalls were designed as monolithically connected with the abutment body. The intermediate supports are designed as pillars with 3 (left-hand carriageway) and 2 pillars (right-hand carriageway) respectively, each of oval cross-section (Fig. 6).

Soil and water conditions and the adopted foundation solution for the flyover supports:

– soil and water conditions: a series of Quaternary sandy formations in the form of fine sands and silty sands occur in the subsoil beneath a soil layer with a thickness of approximately 0.1 to 0.5 m to a depth of 3.9 m. These sands occur in a loose to medium compacted state. Deposits of silty clay and sandy loam are present, Miocene clays occur under the Quaternary sediments. The deeper layer is a silty clay with frequent interbedding of sandy dust and silty sand. The clays are in a hard-plastic and semi-hard-plastic condition. The top of the semi-clastic clay was drilled to a depth of 13.5 to 17.9 m below terrain level. The groundwater was recorded at a depth of 0.4 to 1.8 m.

Fig. 6. General view of the oval columns of one of the supports of the left-hand carriageway of the site under consideration

The foundation of the structure was designed as a direct foundation in the clay layer. In the case under consideration, waterproofing should be an important aspect, as clays are very sensitive to water. This is important as the clay contains interbedding of silty sands, which can suck up water and weaken the strength parameters of the clay, changing its conditions from hard-plastic to plastic. In this case, a swelling phenomenon occurs, with swelling pressures of 150–300 kPa. When water is applied, the unloaded supports are lifted (the stress under the foundation is then less than the swelling pressure), but when the load is applied, this results in the increased settlement of the supports as seen in Fig. 7 and 8.

Fig. 7. Deformation and local depression of the working platform near one of the supports

Fig. 8. Voids under the working platform near one of the supports

4.2. Risk assessment

For the description of the fuzzy functions, a linear scale from 0 to 10 has been adopted. When determining the risk of an event related to the foundations failure, it is necessary to determine the value of the probability of failure as well as the consequence of failure on a point scale from 0 to 10. In the case considered, a point weight has been assigned for the probability of failure of 3 and for the consequence of 7. According to Figure 2, the outputs of the fuzzy decision function are two fuzzy sets:

$R = \{(L, 0.25), (M, 75)\}$and $C = \{(\text{M}, 1{,}0)\}$.

The inference process was carried out according to the defined risk matrix (Table 4), which also forms the basis of the 25 rules. Fuzzy inference requires the determination of the degree of membership of the individual requirements – the higher the degree of fulfillment of the premise (higher degree of membership), the higher the contribution of the rule in question to the determination of the final conclusion based on the rule database. In order to perform the implication operations of the premises of individual rules, the min-max rule was applied.

Fuzzy inference can be divided into four stages [19]:

– determine which rules are included in the risk analysis process from the input mapping: $P_f \times C$, as shown in Table 4; Two rules should be adopted for the analyses, which are the basis for the risk estimation:
  $R1$: If P_f is low and C is medium, then R is low;
  $R2$: If P_f is medium and C is medium, then R is medium;
– carry out actions in each group of rules using the „min" operator; in the example analysed, the values of the membership functions of each rule were:
  $R1$: $\mu R = \mu L(P_f) \wedge \mu H(C) = \min(0.25, 1{,}0) = 0.25$
  $R2$: $\mu R = \mu M(P_f) \wedge \mu H(C) = \min(0.75, 1{,}0) = 0.75$
– determination of the output for individual fuzzy rules (Figure 9)
  $R1$: $\mu R \wedge \mu M(R) = \min(0.25, \mu M(R))$
  $R2$: $\mu R \wedge \mu H(R) = \min(0.75, \mu H(R))$
– fuzzy aggregation
  $\mu R(L) = \max\{\min(0.25, L(R)), \min(0.75, M(R))\}$

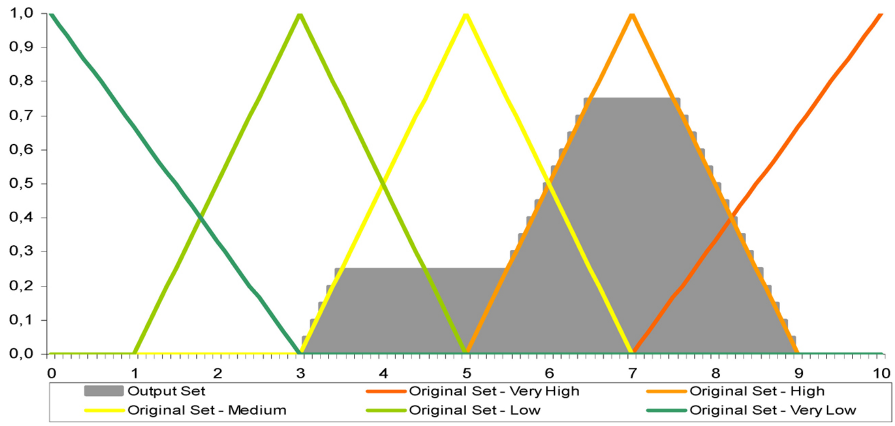


Fig. 9. Output set of risk

The final step is to transform the fuzzy output into a determined risk value, the transformation of the fuzzy set was performed using the singleton method:

$\mu R(L) = \max\{\min(0.25, L(R)), \min(0.75, M(R))\}$

The determined output value of the model, which is an assessment of the foundation risk is:

$$R = \frac{0,25 \cdot 5 + 0,75 \cdot 7}{0,75 + 0,25} = 6,5$$

In the presented analysis of the flyover foundation, the estimated risk, for the probability of failure of 3.5 and consequences defined at level 7, can be defined with a degree of certainty of 0.75 as high risk and with a degree of certainty of 0.25 as medium risk. The determined output value of the model, which is an assessment of the foundation risk, was $R = 6.5$, so this is a risk between medium and high risk.

The determined value of risk using fuzzy sets can provide the risk management project team or the construction contractor with valuable information to make decisions on risk response.

5. Conclusions

This study presented a comprehensive risk assessment model for construction projects, utilizing fuzzy set theory to address the inherent uncertainty and subjectivity in risk analysis. The primary findings demonstrate that fuzzy set theory can significantly enhance the precision and reliability of risk assessments by effectively modeling and interpreting imprecise data and expert judgments. The application of fuzzy inference systems in this context offers a novel approach to integrating qualitative and quantitative information, thereby improving decision-making processes in construction project management.

The strength of this study lies in its innovative use of fuzzy logic to handle the complexity and vagueness that traditional risk assessment methods often struggle with. This approach not only allows for a more nuanced understanding of risk factors but also enables the construction of a more dynamic and adaptable risk assessment model. The importance of this study is underscored by the growing complexity of construction projects and the increasing need for effective risk management strategies that can accommodate uncertain and incomplete information.

However, the study is not without its limitations. The reliance on expert judgments and the subjective nature of fuzzy set categorization can introduce biases and variability in the risk assessment outcomes. Moreover, the model's performance is heavily dependent on the quality and comprehensiveness of the input data, which can be a significant constraint in environments where data availability is limited.

Future studies should focus on refining the fuzzy set theory-based risk assessment model by incorporating more robust data validation and normalization techniques to reduce potential biases. Additionally, exploring the integration of this model with other risk management tools and techniques could provide a more holistic approach to risk assessment in construction projects. Further research is also needed to evaluate the model's applicability and effectiveness across different types of construction projects and risk scenarios, thereby broadening its utility and impact on the field of construction management.

References

[1] D.F. Cooper, D.H. MacDonald, and C.B. Chapman, "Risk analysis of a construction cost estimate", *International Journal of Project Management*, vol. 3, no. 3, pp. 141–149, 1985, doi: 10.1016/0263-7863(85)90065-1.

[2] K.R. Molenaar, "Programmatic Cost Risk Analysis for Highway Megaprojects", *Journal of Construction Engineering and Management*, vol. 131, no. 3, pp. 343–353, doi: 10.1061/(ASCE)0733-9364(2005)131:3(343).

[3] S. French and D. Ros Insua, *Statistical decision theory*. Hoboken, NJ: Wiley, 2000.

[4] L.A. Cox, "Statistical Risk Modeling", in: *Risk Analysis Foundations, Models, and Methods. International Series in Operations Research & Management Science*, vol. 45. Boston, MA: Springer, 2002, pp. 133–215 doi: 10.1007/978-1-4615-0847-2_3.

[5] T. Bedford and R. Cooke, *Probabilistic Risk Analysis: Foundations and Methods*. Cambridge University Press, 2001.

[6] X. Wang and J. Huang, "Risk Analysis of Construction Schedule Based on Monte Carlo Simulation", in *Proceedings of International Symposium on Computer Network and Multimedia Technology*. Wuhan, China, 2009, doi: 10.1109/CNMT.2009.5374816.

[7] J. Nadaf, M. Nadaf, B. Jamadar, and K.P. Thejaswi, "Qualitative Risk Analysis for Construction Projects", *International Research Journal of Engineering and Technology, IRJET*, vol. 5, no. 6, 2018.

[8] A. Hanea, M. McBride, M. Burgman, and B. Wintle, "The value of discussion and performance weights in aggregated expert judgements", *Risk Analysis*, vol. 38, no. 9, pp. 1781–1794, 2018, doi: 10.1111/risa.12992.

[9] A. Hanea, G. Nane, T. Bedford, and S. French, *Expert Judgment in Risk and Decision Analysis*. Cham: Springer, 2021.

[10] A. Hanea and G. Nane, "Editorial: Multivariate Probabilistic Modelling for Risk and Decision Analysis", *Frontiers in Applied Mathematics and Statistics*, vol. 8, art. no. 829729, 2022, doi: 10.3389/fams.2022.829729.

[11] M. Beynon, B. Curry, and P. Morgan, "The Dempster-Shafer theory of evidence: an alternative approach to multi-criteria decision modelling", *Omega*, vol. 28 no. 1, pp. 37–50, 2000, doi: 10.1016/S0305-0483(99)00033-X.

[12] A. Leśniak, D. Kubek, E. Plebankiewicz, K. Zima, and S. Belniak, "Fuzzy AHP application for supporting contractors' bidding decision", *Symmetry*, vol. 10, no. 11, 2018, doi: 10.3390/sym10110642.

[13] I. Skrzypczak, W. Kokoszka, J. Zięba, A. Leśniak, D. Bajno, and L. Bednarz, "A proposal of a method for ready-mixed concrete quality assessment based on statistical-fuzzy approach", *Materials*, vol. 13, no. 24, art. no. 5674, 2020, doi: 10.3390/ma13245674.

[14] A. Leśniak, "Bid assessment with the use of fuzzy sets theory", in *AIP Conference Proceedings*, vol. 1648, no. 1, art. no. 600006. AIP Publishing LLC., 2015, doi: 10.1063/1.4912838.

[15] J. Konior, "Technical assessment of old buildings by fuzzy approach", *Archives of Civil Engineering*, vol. 65, no. 1, pp. 129–142, 2019, doi: 10.2478/ace-2019-0009.

[16] E. Plebankiewicz and P. Karcińska, "Creating a Construction Schedule Specyfing Fuzzy Norms and the Number of Workers", *Archives of Civil Engineering*, vol. 62, no. 3, pp. 149–164, 2016, doi: 10.1515/ace-2015-0089.

[17] E. Plebankiewicz, K. Zima, and D. Wieczorek, "Life cycle cost modelling of buildings with consideration of the risk", *Archives of Civil Engineering*, vol. 62, no. 2, pp. 149–166, 2016, doi: 10.1515/ace-2015-0071.

[18] S. Woliński, "Multi-faced assessment of structural safety", *Archives of Civil Engineering*, vol. 67, no. 2, pp. 133–154, 2021, doi: 10.24425/ace.2021.137159.

[19] J. Zeng, M. An, A.H.C. Chan, and Y. Lin, "A methodology for assessing risks in the construction process", in *Proceedings of 20th Annual ARCOM Conference*, 1–3 September 2004, Heriot Watt University. Association of Researchers in Construction Management, 2004, vol. 2, pp. 1165–1174.

[20] S. Woliński, "Ryzyko w projektowaniu konstrukcji z betonu", *Zeszyty Naukowe Politechniki Gdańskiej*, vol. 602, no. 59, pp. 55–61, 2000.

[21] S. Woliński, "Risk reliability-based design", presented at 11th International Conference on Metal Structures, Rzeszów, Polska, 2006.

[22] G. Harding and J. Carpenter, "Disproportional collapse of Class 3 buildings: the use of risk assessment", *The Structural Engineer*, vol. 87, no. 15, 2009.

[23] T. Vrouwenvelder, R. Lovegrove, M. Holicky, P. Tanner, and G. Canisius, *Risk Assessment and Risk Communication in Civil Engineering*. *CIB Report: Publication 259*. Rotterdam: CIB General Secretariat, 2001.

[24] H. Zhi, "Risk management for overseas construction", *International Journal of Project Management*, vol. 13, no. 4, pp. 231–237, 1995.

[25] P. Thompson and J. Perry, *Engineering construction risks: A guide to project risk analysis and risk management*. London: Thomas Telford, 1992.

[26] R.D. Steenbergen and A. Vrouvenvelder, "Safety philosophy for existing structures and partial factors for traffic loads on bridges", *Heron*, vol. 55, no. 2, pp. 123–140, 2010.

[27] EN 1991-1-7:2008 Eurocode 1 – Actions on structures – Part 1–7: General actions – Accidental actions. European Committee for Standardisation, 2008.

[28] ISO 13824:2009 General principles on risk assessment of systems involving structures. ISO, 2009.

[29] ISO 2394:2015 General principles on reliability for structures. ISO, 2015.

[30] JCSS, Background Documents on Risk Assessment in Engineering, Document no. 1, "Theoretical Framework for Risk Assessment and Evaluation". [Online]. Available: https://www.jcss-lc.org/publications/raie/03_risk_backgrounddoc_theoretical_framework_for_risk_assessment_and_evaluation.pdf. [Accessed: 10. Jan. 2023].

[31] S. Woliński, "Conformity control of concrete strength based on the risk assessment", *Zeszyty Naukowe Politechniki Reszowskiej*, vol. 265, no. 53, pp. 163–169, 2009.

[32] EN 1990:2002 Eurocode – Basis of structural design. European Committee for Standardisation, 2002.

[33] EN 1991-1-1 Eurocode 1: Actions on structures – Part 1–1: General actions – Densities, self-weight, imposed loads for buildings. European Committee for Standardisation, 2002.

[34] J.A.J. Huber, M. Ekevad, U.A. Girhammar, and S. Berg, "Structural robustness and timber buildings – a review", *Wood Material Science & Engineering*, vol. 14, no. 2, 2019, doi: 10.1080/17480272.2018.1446052.

[35] Arup, *Review of International Research on Structural Robustness and Disproportionate Collapse*. London, 2011.

[36] U. Starossek and M. Haberland, "Disproportionate Collapse: Terminology and Procedures", *Journal of Performance of Constructed Facilities*, vol. 24, no. 6, pp. 519–258, 2010, doi: 10.1061/(ASCE)CF.1943-5509.0000138.

[37] EN 1993-1-1:2005 Eurocode 3: Design of steel structures – Part 1–1: General rules and rules for buildings. European Committee for Standardisation, 2005.

[38] EN 1994-1-1: 2004 Eurocode 4: Design of composite steel and concrete structures – Part 1–1: General rules and rules for buildings. European Committee for Standardisation, 2004.

[39] CSA, *Risk Analysis Requirements and Guidelines*. Canadian Standards Association, Department for Communities and Local Government, 1991.

[40] I. Bélyácz and K. Daubner, "Uncertainty of risk and increasing risk of uncertainty in business decisions", *Economy and Finance*, vol. 8, no. 3, 2021, doi: 10.33908/EF.2021.3.2.

[41] K.F. Park and Z. Shapira, "Risk and Uncertainty", in *The Palgrave Encyclopedia of Strategic Management*, M. Augier and D. Teece, Eds. London: Palgrave Macmillan, 2017, doi: 10.1057/978-1-349-94848-2_250-1.

[42] B. Tchórzewska-Cieślak, „Rozmyty model ryzyka awarii sieci wodociągowej", *Ochrona Środowiska*, vol. 33, no. 1, pp. 35–40, 2011.

[43] I. Skrzypczak, *Analiza kryteriów oceny jakości betonu oraz ich wpływu na ryzyko producenta i odbiorcy*. Rzeszów: Oficyna Wydawnicza Politechniki Rzeszowskiej, 2013.

[44] M. Holicky, "Risk assessment in advanced engineering design", *Acta Polytechnica*, vol. 43, no. 3, pp. 10–16, 2003, doi: 10.14311/432.

[45] M.H. Faber, "Framework for risk assessment of structural systems", in *Proceedings of Workshop COST C26: Urban habitat constructions under catastrophic events*. Prague, 2007, pp. 359–367.

[46] A.S. Nowak, "Analiza ryzyka i ocena niezawodności konstrukcji w praktyce budowlanej", in *Proceedings of Awarie Budowlane 2007*. Międzyzdroje, 2007, pp. 123–130.

[47] J. Murzewski, *Niezawodność konstrukcji inżynierskich*. Warszawa: Arkady, 1989.

[48] G.M. Winch, *Managing Construction Projects: An Information Processing Approach*. United Kingdom: Oxford Blackwell Publishing, 2002.

[49] V. Carr and J.H.M. Tah, "A fuzzy approach to construction project risk assessment and analysis: construction project risk management system", *Advances in Engineering Software*, vol. 32, no. 10-11, pp. 847–857, 2001, doi: 10.1016/S0965-9978(01)00036-9.

[50] E. Cox and M. O'Hagan, *The fuzzy systems handbook*. New York: Morgan Kaufmann Books – Elsevier, 1999.

[51] H.X. Li and C.V. Yen, *Fuzzy sets and fuzzy decisions-making*. New York, USA: CRC Press, 1995.

[52] B. Moller and M. Beer, *Fuzzy Randomness: Uncertainty in Civil Engineering and computational mechanics*. Berlin: Springer-Verlag, 2004.

Zastosowanie teorii zbiorów rozmytych w ocenie ryzyka podczas budowy

Słowa kluczowe: ocena ryzyka, macierz rozmyta, systemy rozmyte, konstrukcje inżynierskie, mosty

Streszczenie:

Zastosowanie tradycyjnych technik modelowania ryzyka, takich jak metody statystyczne i probabilistyczne, które stanowią podstawę szacowania i analizy ryzyka nie zawsze są narzędziami efektywnymi ekonomicznie, czy społecznie w budownictwie. Wynika to m.in. z rozbieżności pomiędzy okresem planowania przedsięwzięcia a jego realizacją i trwałością. Powszechnie stosowane są statyczne czy dynamiczne metody pomiaru efektywności przedsięwzięć, a także metody operacyjne, które umożliwiają rozwiązanie problemów w konkretnych sytuacjach decyzyjnych. Uwzględnienie subiektywności oraz brak pełnych i precyzyjnych informacji poważnie ogranicza, a czasami wręcz uniemożliwia zastosowanie tradycyjnych metod. W takim przypadku zastosowanie teorii zbiorów rozmytych, w celu modelowania złożonych zagadnień, takich jak ryzyko wydaje się działaniem pożądanym i uzasadnionym. Zastosowanie zbiorów rozmytych w budownictwie nie jest zagadnieniem nowym. Jednak, większość badań naukowych dotyczących wykorzystania logiki rozmytej w branży budowlanej okazała się albo zbyt uproszczona, albo zbyt szczegółowa, dlatego zaproponowano rozmyte matryce oceny ryzyka. Proponowane alternatywne metody oceny ryzyka oparte są na teorii zbiorów rozmytych przy uwzględnieniu zaleceń normowych. W artykule omówiono także podstawowe informacje dotyczące strategii projektowania konstrukcji budowlanych z uwzględnieniem normowych zaleceń modelowania i oceny ryzyka w budownictwie. Zamieszczono również przykład ilustrujący zastosowanie proponowanej metodologii szacowania jakościowego i ilościowego ryzyka w odniesieniu do obiektu mostowego.

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