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Complex Building's Decision Support Method Based on Fuzzy Signatures [†]

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Abstract: In the inner areas of large cities, many residential buildings built at the turn of the 19th and 20th centuries remain standing. The maintenance and renovation of these buildings have emerged as critical priorities over recent decades. E.g., in Budapest during the socialist era, the majority of these buildings were not renovated, and maintenance was largely neglected. In the subsequent 10–15 years following the end of socialism, financial resources for renovations were scarce due to the extensive transfer of properties from state to private ownership. It is only in the last decade or so that renovations have begun to be systematically addressed. Consequently, a significant portion of the building stock is still pending renovation. Given the current economic conditions, sustainable maintenance and necessary conversion are of paramount importance. Unfortunately, few standardized condition assessment methods are implemented in industrial practice, and the literature on this topic is limited. To address these challenges, we have developed an algorithm and model for condition assessment and decision support, which we refer to as the Complex Building's Decision Support System based on Fuzzy Signatures (CBDF system). Our model employs a fuzzy signature-based approach to account for uncertainties, errors, and potentially missing data that may arise during the assessment process. The primary aim of this model is to equip professionals involved in building condition assessment with a tool that enables them to make consistent and objective decisions while minimizing errors. This paper provides a brief overview of the CBDF system and presents test results from the assessment of a selected structural component of a building, demonstrating the system's functionality.

Keywords: complex framework; fuzzy signature; condition assessment; decision support; apartment building; building renovation; building conversion

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1. Introduction

This paper is an extended version of our paper published in Proceedings of CIRMARE 2023 [1].

Every historical era is characterized by distinctive residential building types constructed using the load-bearing structural solutions and architectural styles prevalent at the time. Budapest, the capital of Hungary, serves as a prime example of the massive urban transformation and dynamic development witnessed by many European cities toward the end of the 19th and the beginning of the 20th centuries.

Because Budapest developed into a metropolis over a short period of time, its growth has differed in many ways from that of other large cities worldwide. Within a few decades, starting in the 1870s, new neighborhoods emerged. The development process utilized unique plans yet resulted in buildings that were strikingly similar in terms of technological solutions and construction materials. This stock of buildings remains largely intact today and constitutes a significant component of the cityscape (see Figure 1).

Figure 1. Typical cityscape of Budapest.

While some structures have undergone consistent maintenance over the past century, the condition of others has drastically declined (see Figure 2). Many of these buildings exhibit static, functional, and social deterioration. Currently, the efficiency of inspection, refurbishment, or conversion of these structures varies significantly, partly because the engineers tasked with these activities possess varying levels of experience, expertise, and methodology.

Figure 2. Street façade (**a**) and courtyard façade (**b**) of a typical old residential building in Budapest.

To mitigate these discrepancies, our aim is to develop a uniform and objective method for the condition assessment and decision support for intervention in these historic buildings. Given the vast number of these buildings, which are generally of a similar age and structural design, and considering that a significant portion of them will inevitably require condition assessment and renovation soon due to natural deterioration, it appears reasonable to develop a computerized method tailored to this specific context. Such a method would not only expedite and simplify the condition assessment process during on-site inspections but also provide experts with additional information and support concerning the building and the construction site, some aspects of which may be unknown even to the most prepared specialists at the inspection site.

Building condition assessment is widely investigated.

Lupășteanu et al. propose a checklist and color code-based method [2]. For site investigations, they use predefined checklists for each building element. They rate the condition of the inspected building elements numerically on a scale of 0–100 in five intervals of 20 values based on the collected data. Each interval receives a color to indicate its severity. The method's novelty is the use of color codes to draw the customer's attention to the most serious problems, as well as the checklist that guarantees the uniformity of field inspections; however, the authors miss proposing uniform rating rules for building elements. Eweda et al. use environmental information as well as structural building data; moreover, they introduce a novel relative weighting technique for aggregating the condition of the building's subsystems [3]. They use a 5-point scale from 0 to 1, where 0 represents a very bad condition. Although the numerical limits of their scaling are similar to those of fuzzy scaling (fuzzy set theory uses infinitely many values from 0 to 1), they use only five discrete values in 0.25 steps, losing the possibility of fine-tuning the results. Straub writes about the Dutch Standard for Building Condition Assessment [4]. He states that "the condition assessment methodology and condition parameters of the standard are meant for the assessment of large-scale property" and cannot be used for the assessment of individual buildings. Cited publications (in accordance with others) agree that there is a lack of a uniform and comprehensive CA methodology. In addition, the need for intelligent computer models and algorithms for efficient and uniform CA is obvious.

Mayo and Karanja discuss the use of various assessments in the industry [5], in addition to comparing existing research to current industry practices.

Piaia et al. presented a BIM-based cultural heritage asset management tool that is useful for decision-making about preserving and valorizing historic buildings [6].

Elhakeem developed an asset management framework for educational buildings with life-cycle cost analysis, in which the decision-making process entails the use of technical, financial, and historical asset data [7].

Uzarsky and Burley emphasize that completing a condition evaluation requires breaking down a structure into its basic pieces in a hierarchical manner. These elements can be organized into several groups using a hierarchical structure. Components can be categorized into a specific branch of the hierarchy to indicate interconnected characteristics [8].

There are many visual inspection-based condition assessment systems in the field of educational buildings [9,10], in the field of monument buildings [11], or in the field of residential buildings [12,13].

Using fuzzy logic for condition assessment and decision-making is not unique.

Deniz Besiktepe et al. introduced a framework that uses multiple variables in the condition assessment process (as opposed to a single source of information, such as visual inspections) and uses fuzzy set theory in the context of facility management and building maintenance.

The received condition rating has the potential to be advantageous for facility management departments as it can aid in prioritizing maintenance tasks, supporting maintenance budget requests, and facilitating decision-making processes [14].

Fayek's study examined fuzzy techniques in construction engineering and management and highlighted fuzzy hybrid techniques with multicriteria decision-making, optimization, machine learning, and risk analysis. In addition, he considered the use of fuzzy techniques very important in situations that involve subjective uncertainty and require expert assessment [15].

Mitra et al. used fuzzy set theory [16] to turn the visual inspection data of corrosion-damaged reinforced concrete building elements into a quantitative condition index. Their research has demonstrated that the acquired condition index can aid in determining whether the evaluated concrete elements require repair.

The application of fuzzy sets theory was utilized to assess the performance of facilities both during and after the construction period [17] and to manage the subjective uncertainty of expert judgment in the process of facility life-cycle cost analysis [18].

Sasmal et al.'s research focused on using fuzzy concepts to assess the state of reinforced concrete bridges [19].

An interesting application of fuzzy logic is used by Bektas and Kegyes-Brassai for the condition assessment of buildings after earthquakes, which provides quick results [20]. Ferenci suggests fuzzy solutions for the classification of industrial floor damages [21], while Sós and Földesi use them for marketing strategy evaluation in logistics decisions [22]. Molnárka and Kóczy proposed a decision support system for valuing existing apartment buildings based on architectural aspects based on fuzzy signature rule bases [23].

Fuzzy concepts were used to model the service-life prediction of reinforced concrete bridge girders [24] and exterior natural stone claddings [25] that can facilitate the development of efficient maintenance programs. Lendo et al. proposed an assessment of the technical condition of heritage buildings with the use of fuzzy logic [26]. Marzouk and Award developed a performance evaluation methodology that school administrators can use to assess school conditions. The fuzzy model is a representation of property conditions using linguistic phrases [27].

Cited publications (in accordance with others) agree that there is a lack of a uniform and comprehensive condition assessment methodology. In addition, the need for intelligent computer models and algorithms for efficient and uniform condition assessment is obvious.

Compared to the methods and procedures described in the literature, our proposed method provides the following innovations:

- It is applicable to a large but specific stock of buildings;
- A similarly complex framework has not yet been developed for this type of building stock;
- By using fuzzy sets, we can model not only the general uncertainties associated with condition assessment but also integrate uncertainties based on the applied testing methods and observed errors and anomalies;
- The method not only performs condition assessments based on input data but also provides continuous and immediate feedback to the surveying expert on potential input data error anomalies and, based on the analysis of input data and the knowledge base, alerts to any tests or measurements that require particular accuracy or attention, thereby reducing the possibility of errors during on-site inspections;
- It assesses the condition of individual structures while also considering the interactions among separate structures in the assessment, and based on these interactions, it can modify the requested tests/measurements.

We have developed a method capable of managing uncertainties, supervised inspections, and complex condition assessments of older residential buildings. We describe a decision-making framework specifically designed for building types with unique characteristics, offering a versatile, advanced decision-support solution. Fuzzy models are highly effective in handling uncertainties and addressing potentially missing data.

We have constructed a decision model that can be employed to achieve multiple objectives. The ultimate goal is to empower the expert to conduct the condition assessment and make the intervention decisions with a system that is accessible during the on-site inspection and tests—even via a tablet. By uploading the gathered information into the system, the decision model can provide real-time recommendations for further testing and measurement as needed, offer feedback on detected errors and anomalies, and highlight the need for enhanced precision in any measurement or testing procedure.

The system requests only the data and tests necessary to fulfill the task, optimizing test depth based on the task's objectives. The primary goal of the developed system is to assist the expert through decision support; however, it merely offers recommendations based on the available data, allowing the expert to override these suggestions at any time.

The decision model provides a specific outcome (a fuzzy value and a linguistic value upon defuzzification) for each building under examination, considering the stated objectives. It can also compare the results from multiple buildings when several are inspected, thereby organizing the results systematically.

We have developed a framework that achieves all objectives we consider significant, owing to its logical structure. Parts of this system have been explored in our previous research, and we used the insights gained from these studies to inform the development of this decision model [28,29]. Compared to previous publications of our framework and results, with special regard to our last publication [1], this article presents the CBDF system in much more detail with more examples, and it also contains new experimental results.

Our long-term goals include refining the decision model detailed in this article to its final iteration and developing a fully operational condition assessment and decision support system suitable for market environments, addressing real-world building challenges.

2. Methodology

2.1. System Structure

A framework designed to aid in intervention decision support and the evaluation of conditions in residential buildings has been developed. This framework is referred to as the Complex Building's Fuzzy Signatures-Based Decision Support System (CBDF system). Figure 3 shows the diagram of the CBDF system. The framework has been constructed to satisfy every objective outlined within this structure and to enable future, in-depth development of each of its component sections.

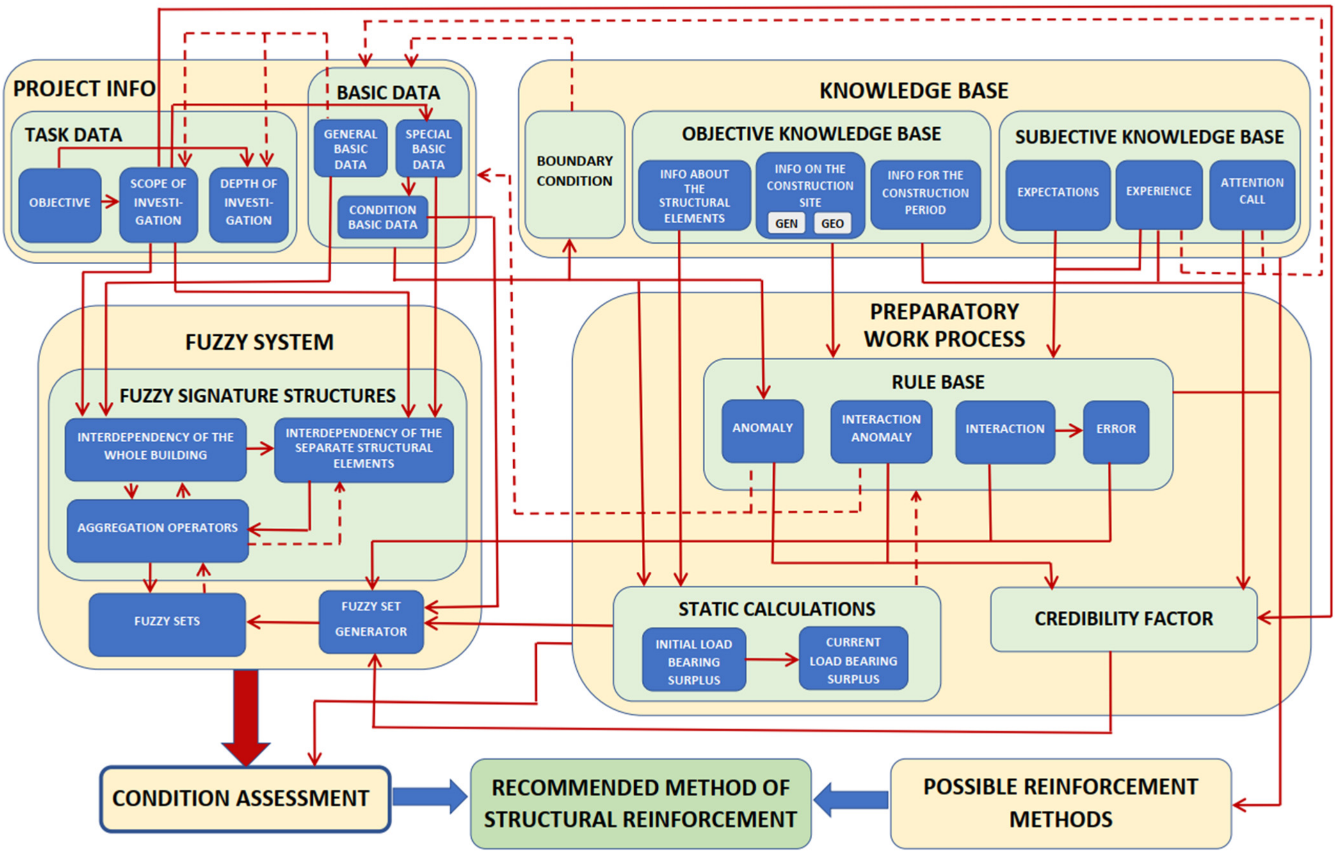

Figure 3. Diagram of the CBDF system.

There are four main components that are integral to obtaining the results of the condition assessment.

"Project info" (PI) includes details about the residential building currently under examination and includes two component blocks. The "task data" specifies the task to be completed and its depth, while the "basic data" contains information and findings related to the building under examination, its structural components, and the conducted tests.

In the "knowledge base" (KB), data fed into the decision model during its creation are stored. It includes three main components. The applicability of the decision model is confined by the "boundary condition". All relevant, objective information is housed in the "objective knowledge base". Information that is subjective yet expert regarding building structures, building diagnostics, building pathology, and condition assessment is contained in the "subjective knowledge base".

The foundations of the "preparatory work process" (PWP) are formed by PI and KB. The role of the "rule base" (RB) component block is to investigate errors, anomalies, and relationships between various construction structures. The "static calculations" (SC) component block is tasked with computing the load-bearing surplus of the pertinent load-bearing structures, which assists in assessing the severity of damage to each specific load-bearing structure. The "credibility factor" (CF) is responsible for evaluating and controlling the uncertainties in the condition assessments using the "project info", "knowledge base", and "rule base".

The "fuzzy system" (FS) initially constructs the appropriate fuzzy signature structure of the analyzed building using "project info" data. A fuzzy sub-signature structure is then allocated to each necessary building structure based on the "special basic data". The results of the "condition basic data" and the "preparatory work process" are used to prepare the required fuzzy set descriptor and to identify the suitable aggregation operators within the fuzzy signature structures. The condition assessment is completed by defuzzifying the findings of the fuzzy signature and incorporating certain outcomes of "preparatory work process".

2.2. Project Info

It includes the essential information about the residential building (project) currently under examination, which is required for conducting a thorough condition assessment according to the intended objective. For each scenario, the data are supplied by the specialist who conducts the condition assessment using the information gathered about the structure.

2.2.1. Task Data

In the "task data" (TD), the expert determines the goal of the condition assessment, the types of structures to be evaluated, and the depth of the inspections.

The purpose of the condition assessment is defined by the "objective" (OBJ). Examples of objectives include assessment of the general load-bearing structural, optimization of renovation (optimal use of available financial resources), determination of whether urgent intervention is needed to avoid rapid deterioration, investigation from the aspect of accident and risk to life, condition inspection due to the intention to demolish the building; examination of sensitivity to earthquakes, examination of the possibility of adding additional story(s), and examination of the feasibility of roof installation.

The "scope of investigation" (SOI) delineates the specific structures within the building that require evaluation. There are three possible scenarios: a comprehensive study of all structures (global), an examination of a single structure (local), or an analysis of multiple structures, though not all (multi). Typically, the decision regarding which building structures need evaluation is typically made by the expert. However, in many instances, the objective of the condition assessment clearly and automatically indicates it. For example, if the objective is to assess the suitability or conformance of the building for roof installation, the system automatically selects the roof structure, attic floor structure, wall structure, and foundation structure for examination. This selection is based on the fact that the outcome predominantly depends on their design and condition, whereas other load-bearing structures are of lesser importance to the investigation.

There are three different levels of "depth of investigation" (DOI), each varying in the amount of time and effort invested. The rapid level involves a visual examination that is supported by essential geometric measurements. The detailed one is exceptionally precise, encompassing meticulous measurements, instrumental assessments, on-site inspections, and, if required, even destructive and laboratory tests. Between these lies the semi-detailed examination. Although time-consuming, the detailed examination is significantly more reliable compared to the rapid examination. This difference is taken into consideration when determining the "credibility factor".

2.2.2. Basic Data

Basic data include the crucial data needed to prepare a condition assessment tailored to the building under review and its intended purpose. Following an analysis of the "task data", the system requests the importation of particular data. Nonessential data that are unknown or can only be obtained indirectly may be omitted (not available). The utilization of fuzzy signatures in condition assessment offers a notable advantage by providing results even in the case of missing data. This aspect is considered partially in the "credibility factor" and partially in the "fuzzy system" main component.

The "basic data" (BD) component block comprises three elements: "general basic data" (GBD), "special basic data" (SBD), and "condition basic data" (CBD).

The GBD includes building-specific data such as building location, construction year, number of floors, level of sub-basement, and dimensions of building parts.

Considering the objective, SBD includes pertinent information from the perspective of each building structure that needs to be evaluated (e.g., foundation structure, intermediate floor structure, side corridor structure, roof structure). For intermediate floor structures made of steel joists, relevant data may include, for example, the dimensions of the floor, the spacing between the floor beams, and the width of the flange of the I-section steel joists.

The CBD contains information gathered from the condition inspections of the pertinent load-bearing structures. For floor structures constructed with steel joists, relevant information may include, e.g., the position and extent of corrosion in the steel joist, as well as inspections to determine the hardness of the steel joist.

The system only requests data from the expert that is necessary for the objective of the task.

2.3. Knowledge Base

The development process of a decision model involves the definition and uploading of data into the knowledge base. This database contains the boundary criteria and known data essential for assessing the state of historic residential buildings. The data presented here are sourced from professional expertise, expert reports, and specialized literature (e.g., [30,31]).

2.3.1. Objective Knowledge Base

The "Objective Knowledge Base" (OKB) comprises information that is entirely objective, devoid of any influence from expert subjectivity. We differentiate between three key elements within the OKB.

"Info about the Structural Element" (OKB-ISE): This includes potential material properties, dimensions of the sections, and contemporary tables indicating the load capacity [32]. For instance, it is known that steel sections used in Budapest at the turn of the 19th century to the 20th century were predominantly sourced from two Hungarian steel factories. Understanding the section selection of these factories allows us to import exact geometric dimensions of these sections into the knowledge base. This availability significantly aids experts during building examinations by facilitating their work and reducing the probability of incorrect structural determinations.

"Info on the construction site" (OKB-ICS): This element is divided into two main groups: "General Map Info" (ICS-GEN) and "Geotechnical Map Info" (ICS-GEO), both of which provide crucial site-specific information through map visual representations.

ICS-GEN contains the following map figures:

- Urban development timelines;
- Location of significant war events;
- Architecturally protected areas (e.g., world heritage site, local protection);
- Property plot values;
- Noise and vibration effects from nearby transit sources.

For example, a map detailing urban development can provide data on the earliest possible construction date for a building, helping to prevent data entry errors regarding building ages. Additionally, maps indicating wartime events are critical as they suggest potential structural damage, necessitating more intensive investigations to accurately determine structural integrity. (This is very important information since in the partial reconstructions after the wars, the load-bearing structure system and materials used at the time of construction were no longer used, so it can be assumed that, e.g., a floor structure is made with several types even within one level.)

ICS-GEO includes the following:

- Area with high or aggressive groundwater;
- Earthquake hazard aspects;
- Regions with volume-changing clay soils;

- Areas prone to slipping.

These maps include geotechnical data, which, even in the absence of a comprehensive soil test report, can offer estimated information on crucial soil mechanical and groundwater properties of the construction site. Based on these data and the type and extent of damage detected on the building, the system can suggest to the expert whether it is necessary to prepare a soil excavation afterward.

ISC-GEO provides important additional information in decision-making, such as determining whether it is feasible to add a story or install a basement, under what conditions these modifications can be made, and whether it is necessary to strengthen the foundation, including methods for doing so.

"Info on the Construction Period" (ICP): This gathers data on specific features of the construction period that could have impacted the design and quality of the structure. For example, if the construction year of the building is known, the system automatically assigns the standards used at the time of construction and the relevant information (for example, the imposed load required by the given standard). Since the first standard was published in Hungary in 1892 (Building Regulations in the capital city of Budapest), if an examined building was built earlier than that, the system can handle uncertainties derived from the lack of regulation.

The period of usage of each building material (e.g., limestone plates, slag concrete, steel sections, large-size brick) is also a crucial piece of information. As an example, slag concrete load-bearing constructions were only utilized in Hungary from 1893 to 1920. Therefore, it is improbable to find this construction material in buildings constructed outside of this timeframe. If a building was constructed outside of the specified era as determined by the GBD and also has a slag concrete structure according to the SBD, then it is likely that either the year of construction or the building material of the load-bearing structure was wrongly recorded in the BD.

The system already draws the expert's attention to this when uploading PI, and if the input data are not modified, the resulting uncertainty is also considered (by modifying fuzzy sets) in the condition assessment.

2.3.2. Subjective Knowledge Base

The "subjective knowledge base" (SKB) comprises information that, while reliable and accepted by the profession, is derived from the subjective judgments of the experts who developed the decision model. It includes three elements: "expectations" (SKB-EC), "experience" (SKB-EP), and "attention call" (SKB-AC).

Subjective limit values are part of SKB-EC, and the system will signal an error if these are not met. These limit values are established by specialists who develop the decision model using their expertise and recommendations from literature (as opposed to, e.g., the density of steel included in OKB-ISE, which is objectively 78.5 kN/m^3). If the building being assessed has a value more advantageous than one of the expectations, the system can enhance the estimated condition of the structure. Conversely, if the value is less favorable, the condition is considered deteriorated (e.g., the minimum overlap of the timber floor joist on the wall structure is 15 cm).

The residential buildings under examination reveal the geometric proportions, section sizes, material quality, and connection types employed over various construction periods, as well as the specific building structures they were used for. These values are stored in the "experience" (SKB-EP) element. A failure to meet these conditions does not necessarily indicate a problem in the reviewed load-bearing structure. It is more likely that a mistake occurred during the input of basic data or that the examined structure was constructed in a manner that deviated from the prevailing norms at the time. For instance, in the SKB-EP, we record the minimum and maximum section sizes and spans used for each type of timber roof structure.

The "Attention Call" SKB-AC comprises data that are either insufficient for a clear identification on their own or that are easily mistaken with other building materials, sections, or support structure systems. If any measurements or other data are input into the system (BD) during on-site inspections that correspond to any of the data in the SKB-AC, the system will issue a warning to the expert who is conducting the condition assessment.

For example, in the case of a steel beam floor or steel cantilever side corridor, the steel section can usually be clearly identified from the width of the bottom flange of the I-section (this measurement can be easily performed on-site). However, if the flange width is measured to be 90 mm, the profile could be either 180 mm high (following the old Hungarian standard, MSZ) or 200 mm high (following the old German standard, DIN). The load capacity of the two sections differs, and both types of sections were often used in residential buildings in Hungary. In such cases, the system requires an additional geometrical measurement to clearly identify the steel section.

2.3.3. Boundary Condition

The "Boundary Conditions" (BC) encompass the prerequisites necessary for the validity of the system produced. For example, the method is appropriate for evaluating residential structures constructed between the years 1850 and 1950, which have a maximum of five levels.

2.4. Preparatory Work Process

This process prepares fuzzy sets and conducts condition evaluations using data from PI and KB.

2.4.1. Rule BASE

The rule base (RB) is a compilation of rules that can be defined using logical operations (IF, AND, OR, THEN) and consists of four components: "error", "anomaly", "interaction", and "interaction anomaly".

An "error" (RB-E) always indicates a contradiction or an inadequate solution. For example, an error occurs when the overlap of the timber floor joist on the wall structure is smaller than 15 cm.

An "anomaly" (RB-A) identifies atypical, exceedingly uncommon, and peculiar solutions, indicating the possibility of an input error. In such instances, the system highlights the input data that may be erroneous. For example, the system indicates an anomaly if, based on the SBD, the wall of a building constructed before 1929 is made of small-size bricks, which were not produced in Hungary until 1929. In such cases, the system draws attention to potentially incorrect input data, such as the year of construction or the material of the wall (incorrectly measured wall thickness) that was imported into the system. It is possible that the presence of small bricks is due to subsequent reconstruction.

"Interaction" (RB-I) focuses on the interplay between two building structures. It frequently occurs that the structural condition or design of one building structure influences the structural condition or design of another. Under such circumstances, the system documents these observations and considers them during the analysis of the relevant load-bearing structures. For example, if the side corridor slopes inward (toward the wall structure), rainfall and snow can damage both the wall and the floor structure (serious damage can occur where the steel beam or timber beam bears on the wall). This consideration is incorporated into the condition assessment of both the wall and the floor structures (Figure 4). For example, if the related floor structure is steel joist floor, then the system requires a corrosion test at the tailing of the steel joist, while if the related floor structure is timber joist floor, the system requires a decay test of the timber joist at the tailing (where moisture can affect the joists).

An "Interaction Anomaly" (RB-IA) occurs when the input data for one structural element are not compatible with the input data for another structural element. Although there is no contradiction between the two datasets (the case is not impossible), it represents a very rare and unusual solution. The system also sends a notification to the expert conducting the condition assessment. For example, if the SBD indicates an intermediate floor with steel joists and the side corridor has stone cantilever, the system indicates that the likelihood of this solution is low. This is because when steel beam floors became widespread, the use of stone cantilevers in side corridors typically ceased. Instead, side corridors with steel cantilevers, often covered with gypsum rabitz, which mimics the appearance of stone, became common.

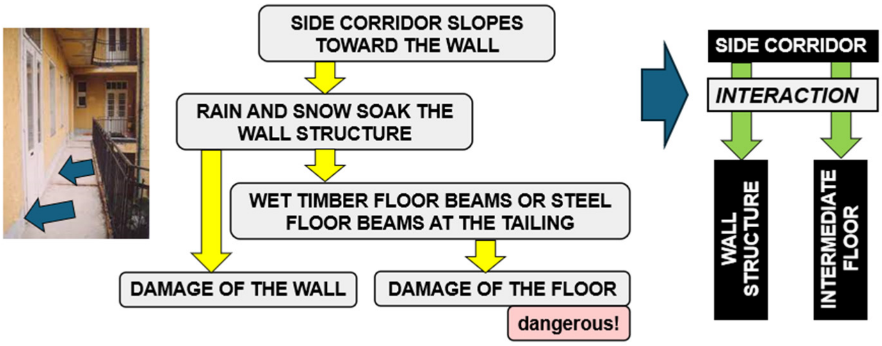

Figure 4. An example of the interaction between the side corridor, the wall structures, and the floor structures.

2.4.2. Static Calculations

The primary objective of "Static Calculations" (SC) is to ascertain the degree to which the analyzed load-bearing structures were over-dimensioned during their construction. Determining the load-bearing capacity surplus is crucial when assessing how much damage to the load-bearing structure would impact its condition. For instance, when the load-bearing surplus of a steel segment is minimal, even a small amount of corrosion can lead to substantial damage. However, when there is a substantial excess of load-bearing capacity, a minor degree of corrosion has minimal impact on the structural load capacity.

The system automatically calculates the load-bearing capacity and shares that information with the expert via the BD and the KB. Based on this knowledge, a proposal is made to the expert regarding which condition checks are justified and the level of detail/accuracy with which they should be carried out.

The decision model can determine the load-bearing capability using two different methods. The "Initial Load Bearing Surplus" (ILBS) is determined by utilizing the pertinent data of the GBD, SBD, and OKB-ISE, assuming the original error-free condition. The "Current Load Bearing Surplus" (CLBS) is determined by considering the impact of strength loss and cross-section reduction caused by damage, resulting in reduced cross-section and strength characteristics. This calculation utilizes the required data from GBD, SBD, CBD, and OKB-ISE (Figure 5).

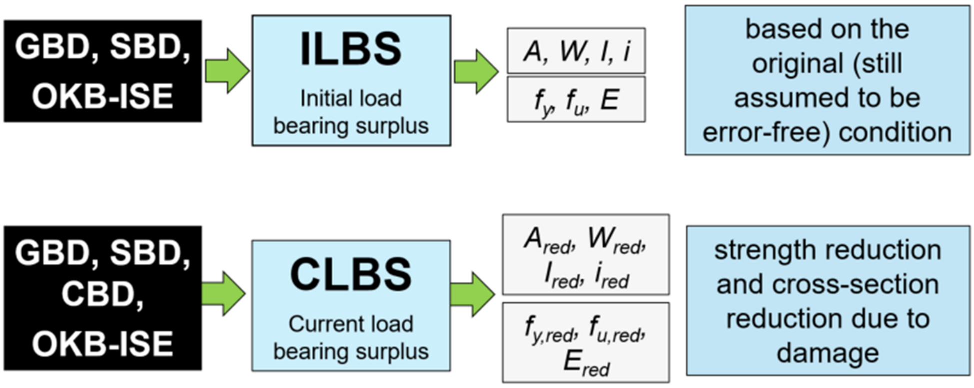

Figure 5. Determining the load-bearing surplus.

2.4.3. Credibility Factor

The "Credibility Factor" (CF) quantifies the level of reliability associated with the outcome of the condition assessment. The credibility level of the condition evaluation is significantly impacted by the following factors:

- DOI: Options include rapid, semi-rapid, and detailed;
- Missing BD: The number and significance of data that the experts are unable to supply;
- GBD considerations: For example, whether the structure underwent a major renovation and whether the original designs still exist;
- Rule base anomalies: The number and importance of RB Anomalies, RB Interaction Anomalies, and RB-Errors;
- Test methods were used for data contained in the CBD since the reliability of different test methods varies greatly.

2.5. On Fuzzy Set Theory and Fuzzy Logic

2.5.1. Fuzzy Sets and Systems

In 1965, Zadeh proposed the application of a novel set-theoretic system, distinct from traditional set theory, in which an object's relationship to a set is binary—being either a member or not [33]. Zadeh's system introduces the concept that an element's membership in a particular set can assume any value within the range of [0, 1], indicating degrees of membership rather than a binary status. Consequently, all elements from the universal set are considered members of all sets to varying degrees. Due to the challenge of defining precise boundaries for these sets, they are termed 'fuzzy sets'.

Fuzzy sets can be represented through a list that specifies each element and its corresponding membership value or, more formally, through their membership functions. A fuzzy set's membership function maps elements from an ordered input space to their membership values in the set.

The distinction between traditional sets and fuzzy sets can be illustrated using the following example. Let T be a traditional set of tall people, defined by a specific cutoff height, say 180 cm (Equation (1)):

$$T = \{\text{person } \left| \text{person}'\text{ s heilght } \right. \geq 180 \text{ cm}\} \tag{1}$$

Next, let F be a fuzzy set of tall people (Equation (2)), where membership is determined by a membership function, $\mu_F(h)$ (Equation (3)), that assigns a value between 0 and 1 based on height h.

$$F = \{\text{person}, \ \mu_F(h)\} \tag{2}$$

$$\mu_F(h) = \begin{cases} 0 \mid h < 170 \text{ cm} \\ \frac{1}{20}h - 8.5 \left| 170 \text{ cm } \leq h \geq 190 \text{ cm} \right. \\ 1 \mid \text{otherwise} \end{cases} \tag{3}$$

According to the characteristic function of set T, an individual 179 cm in height is categorized as not tall, a classification that may not align with common human perception. In contrast, the fuzzy representation of 'tall' heights through the fuzzy set F offers an approach more consistent with human reasoning. These differences are illustrated in Figure 6.

Mirroring the infinite spectrum of fuzzy membership values, operators within fuzzy sets—such as union and intersection—may be represented by an infinite array of functions. However, it is imperative that these operators adhere to established axioms [34]. Among the most prevalent, introduced by Zadeh, are the minimum operator for fuzzy intersection (t-norm) and the maximum operator for fuzzy union (t-conorm). Given that set operators can also function as logical operators, the utilization of fuzzy sets and operators facilitates the efficient construction of complex logic systems. Although the CBDF system employs fuzzy reasoning, this paper does not cover these components; thus, delving into the theoretical background of fuzzy inference systems falls outside its scope.

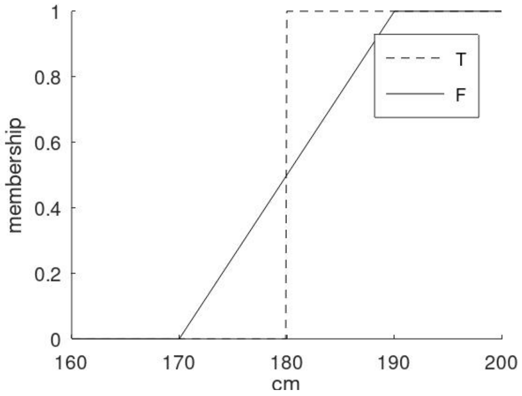

Figure 6. Comparative illustration of deterministic and fuzzy functions for sets *F* and *T* representing tall heights.

2.5.2. On Fuzzy Signatures

Although simpler compared to traditional logic-based systems, fuzzy inference systems can present complexity in various scenarios. For situations where the goal is not to evaluate complex logical statements but to assess the overall state of a complex structure, fuzzy signatures prove to be more advantageous.

A fuzzy signature is a structured representation that extends the concept of fuzzy sets to capture more complex, hierarchical information. While a fuzzy set allows for degrees of membership for elements within a set, a fuzzy signature goes further by organizing these elements into a structured format. This format can represent the multifaceted attributes and their interrelationships within a system or an entity. Fuzzy signatures were introduced by Kóczy [35] and are characterized as specialized fuzzy vectors composed of elements that may either be singular fuzzy values or further nested fuzzy vectors. This composition enables a multi-layered and complex architecture.

Fuzzy signatures can be interpreted as tree structures, representing a hierarchical organization. Within these structures, the terminal nodes, or 'leaves', represent elements devoid of substructures, whereas the 'branches'—elements with substructures—encapsulate not only the values of their constituent leaves but also employ specific operators for their synthesis. These pivotal operators, integral to computing the aggregated values of branches based on their associated elements, are known as aggregation operators. Notably, the Weighted Relevance Aggregation Operator (WRAO) is highlighted as a quintessential example (Equation (4)) [36].

$$@(x_1, x_2, \ldots, x_n; w_1, w_2, \ldots w_n) = \left(\frac{1}{n}\sum_{i=1}^{n}(x_i w_i)^p\right)^{\frac{1}{p}}, \tag{4}$$

where x_i is the ith element out of n, w_i is the weight of the ith element, and p is a power factor.

In the CBDF system, a broad spectrum of fuzzy signatures is deployed to depict the structural elements of buildings. This paper specifically leverages stone plate structures in side corridors as an example to elucidate the system's capabilities. Accordingly, Figure 7 offers a graphical depiction of the fuzzy signature for the condition of stone plates, serving as an apt exemplar. Notably, the figure illustrates not only the dependencies among elements but also delineates the aggregation operators, thereby offering a comprehensive view of the underlying methodology.

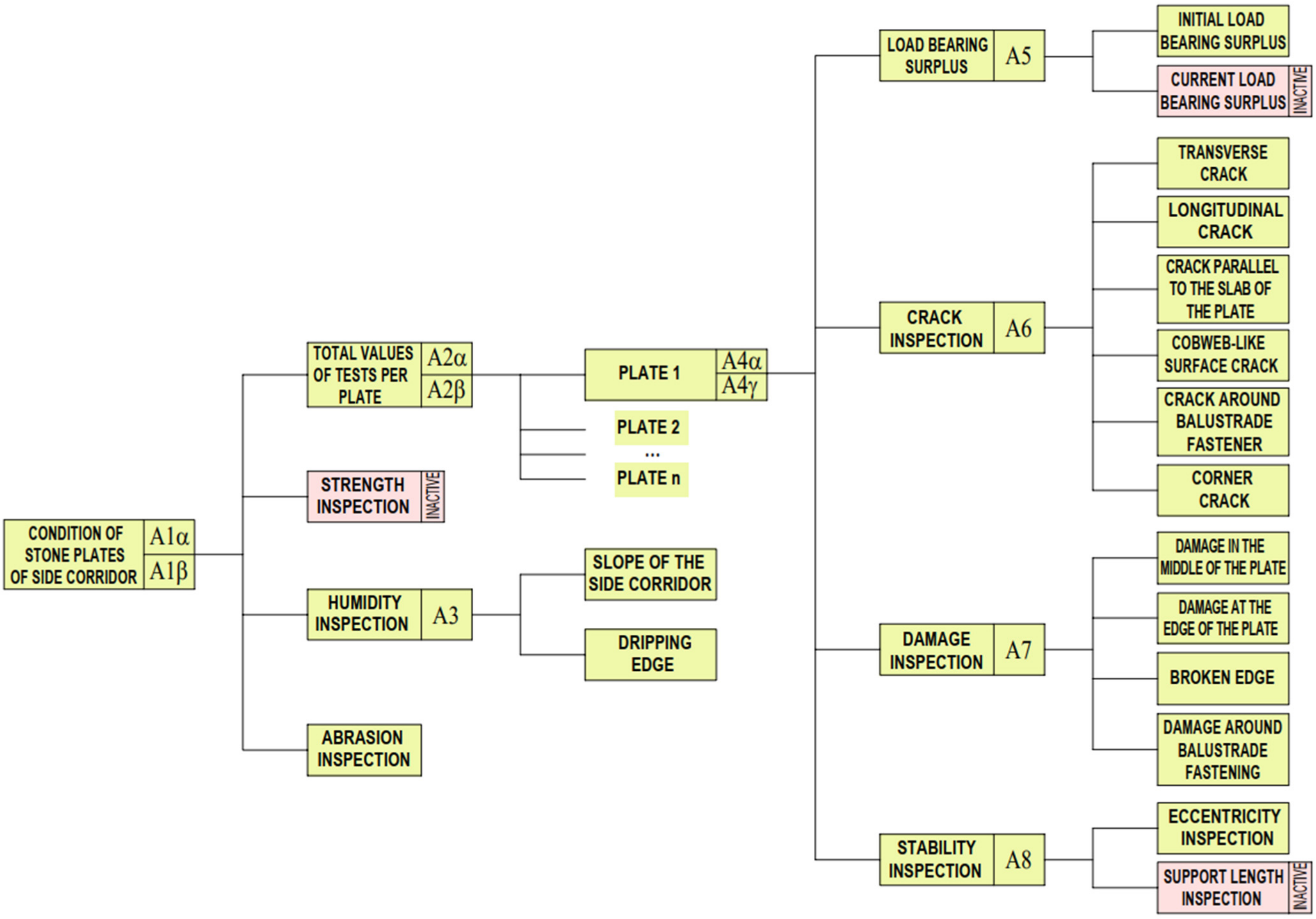

Figure 7. Fuzzy signature structure of the side corridor stone plate.

2.5.3. The Model's Fuzzy Signature

Due to length constraints, detailing the entire system within this paper is not feasible. However, an overarching schematic of the system can be provided for clarity. Figure 8 displays the simplified fuzzy structure of load-bearing structures, deliberately omitting the subordinate structures associated with each node to maintain brevity and focus. Meanwhile, Figure 7 presents a detailed view of a specific part of the system.

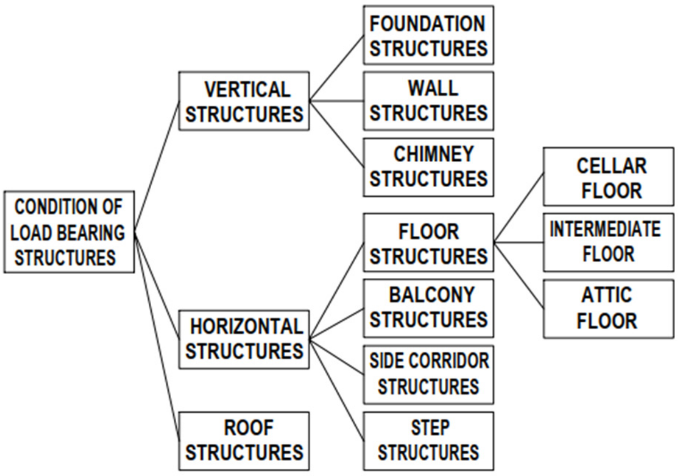

Figure 8. Interdependencies between the load-bearing structures.

3. Experimental Results

As an example, through the examination of a specific residential building, we briefly demonstrate how the CBDF system performs the condition assessment of a selected load-bearing structure, specifically the side corridor stone plate, in Building 1.

In the "Task Data", the expert selects the "Objective" (in this instance, the general load-bearing structural condition assessment), the "Scope of Investigation" (the side corridor), and the "Depth of Investigation" (semi-detailed).

Subsequently, the system requests only the information from the "Basic Data" that is relevant for the examination of the side corridor. Table 1 presents general, geometrical, and condition data for Building 1. The table is not comprehensive; it displays only the data necessary for the examination of the limestone plates. It indicates that the examined building has a side corridor on two floors, and there are seven stone plates per floor.

Table 1. Data from Building 1 in project info.

Task data (TD)	OBJ		GLBSC	(general load bearing structural condition assessment)
	SOI		LOCAL, SC	(side corridor)
	DOI		SD (semi-detailed)	strength test, support length inspection, CLBS are ignored
Basic data (BD) *	GBD		Address (ADR)	Building 1.
			Year of construction (YOC)	1895
			Floor numbers (n_{floor})	3
	SBD		SC	
			Type of SC (TSC)	stone cantilever, stone plate
			Number of SC-s (n_{floor}-1)	2
		COL	Width of SC [cm]	100
		COL	Thickness of stone plates [cm]	12
			Number of stone cantilevers (A)	7
			Number of stone cantilevers (B)	7
			Number of stone plates (A)	7
			Number of stone plates (B)	7
		COL	Stone plate material	limestone
		COL	Width of stone cantilever [cm]	20
		IND	Stone plates length [cm]	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Edge plates (EP) (Y/N)	2*7 db (PA01-PA07) (PB01-PB07)
	CBD		SC	
		COL	Dripping edge (DE) (Y/N)	N
		COL	Slope of the side corridor (SOSC) [%]	0.2°
		COL	Plate support on the wall	N
		COL	Abrasion inspection	15%
		IND	Reinforcement (RF)	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Strutting (ST)	2*7 db (PA01-PA07) (PB01-PB07)
			Crack inspection	
		IND	Transverse crack	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Longitudinal crack	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Crack parallel to the slab of plate	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Cobweb-like surface crack	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Crack around balustrade fastening	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Corner crack	2*7 db (PA01-PA07) (PB01-PB07)
			Damage inspection	
		IND	Damage in the middle of the plate	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Damage at the edge of the plate	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Broken edge	2*7 db (PA01-PA07) (PB01-PB07)
		IND	Damage around balustrade fastening	2*7 db (PA01-PA07) (PB01-PB07)
			Stability inspection	
		IND	Eccentricity inspection	2*7 db (PA01-PA07) (PB01-PB07)

* The basic data contains only the information that is necessary for the semi-detailed examination of the stone plates of the side corridor.

Based on the BD data, the system automatically selects the necessary fuzzy signature structure (Figure 7). The figure shows that some leaves are inactive because the "semi-detailed" investigation was selected instead of "detailed". A1–A7 are the aggregation operators.

Since the stone plates of the side corridors are simple supported plates that are independent of each other in many aspects, certain inspections must be carried out separately for each plate (e.g., crack inspection), while other inspections are performed uniformly for the entire side corridor (e.g., humidity inspection).

Each leaf of the tree structure is assigned a fuzzy set, while each branch has one or more aggregation operators. Among the fuzzy sets required for the condition assessment of the stone plates, we present those related to load-bearing surplus, the slope of the side corridor, and the dripping edge (Figure 9). Among the aggregation operators used, the one summarizing the independent inspections of the stone plates (A4) and the one for crack inspection is illustrated (A6) (Equations (5) and (6)).

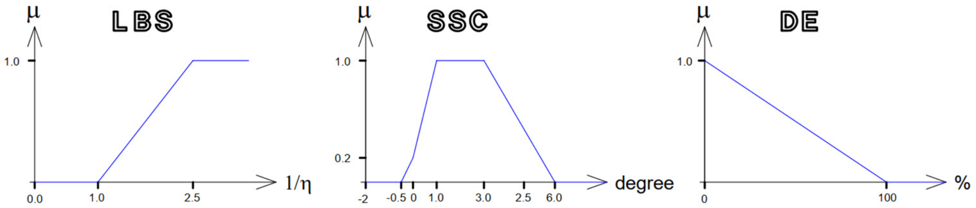

Figure 9. Fuzzy sets for load–bearing surplus, slope of side corridor, and dripping edge.

Since, in the case of various situations, several branches of the decision tree influence the final decision differently, in their case, state-dependent dynamic weighting is employed. For instance, in scenarios where there is a high vibration level, such as when a metro line runs beneath a building, the impact of corrosion is more significant compared to a building located far from any metro line.

For the calculation weights for the A4 aggregation operator, we use state-dependent dynamic weighting:

$$\begin{gathered} A4\propto=\left(\alpha_{\mathrm{crk}}\cdot\kappa_{\mathrm{crk}}\cdot\kappa_{\mathrm{vib}}\cdot A6+\alpha_{\mathrm{dmg}}\cdot A7+\alpha_{\mathrm{stb}}\cdot A8\right)\cdot\kappa_{\mathrm{lbs}}\cdot\kappa_{\mathrm{st}} \\ \left(\alpha_{\mathrm{crk}}=0.6;\ \alpha_{\mathrm{dmg}}=0.2;\ \alpha_{\mathrm{stb}}=0.2\right) \end{gathered} \tag{5}$$

$$A4\gamma=max\begin{pmatrix} A4\propto; \\ \kappa_{rf} \end{pmatrix}, \tag{6}$$

The values of κ_{crk}, κ_{vib}, κ_{lbs}, κ_{st}, and κ_{rf} are obtained from the following rule base:

- IF A6 $\geq$ 0.6 AND A5 $\geq$ 0.5 THAN κ_{crk} = 1.1 (crk $\leq$ 1.0)
- IF A6 $\leq$ 0.3 AND 0 $\leq$ A5 $\leq$ 0.2 THAN κ_{crk} = 0.9
- in any other case κ_{crk} = 1.0
- IF VIB = 1 THAN κ_{vib} = 0.9
- IF VIB = 1 AND EP = 1 THAN κ_{vib} = 0.8
- IF VIB = 0.5 AND EP = 1 THAN κ_{vib} = 0.8
- IF VIB = 0 AND EP = 1 AND A6 $\leq$ 0.5 THAN κ_{vib} = 0.9
- in any other case κ_{vib} = 1
- IF 0 < A5 < 0.05 THAN κ_{lbs} = 0.7
- IF 0.05 $\leq$ A5 < 0.15 THAN κ_{lbs} = 0.9
- IF 0.15 $\leq$ A5 < 1 THAN κ_{lbs} = 1
- IF A5 = 1 THAN κ_{lbs} = 1.1
- IF A5 = 0 THAN κ_{lbs} = 0
- IF ST = 1 THAN κ_{st} = 0
- IF ST = 0 THAN κ_{st} = 1
- IF RF = 1 THAN κ_{rf} = 0.8
- IF RF = 1 AND ST = 1 THAN κ_{rf} = 0
- IF RF = 0 THAN κ_{rf} = 0

where α_{crk} is the base weight of the cracks, α_{dmg} is the base weight of the damages, α_{stb} is the base weight of the stability, κ_{crk} is the modifying factor depending on cracks, κ_{vib} is the modifying factor depending on vibrations, κ_{lbs} is the modifying factor depending on the load-bearing surplus, κ_{st} is the modifying factor depending on strutting, κ_{rf} is the modifying factor dependent on reinforcement, and A4α is the aggregation operator of the individual stone plates. A6 is the aggregation operator of the crack inspection, A7 is the aggregation operator of the damage inspection, and A8 is the aggregation operator of the stability inspection. A4γ takes into consideration that if the stone plate has been reinforced, then its condition is deemed correct. VIB gives the degree of vibration affecting the building, EP identifies whether the examined stone plate is an edge plate, and RF and ST provide information on whether the examined plate is reinforced or strutted.

Aggregation operator A6 provides the results of the crack inspection and can be calculated using the formula represented by Equation (7).

$$\begin{gathered} A6 = min\begin{pmatrix} \propto_{\text{tcr1}} \cdot tcr + \propto_{\text{crpsp1}} \cdot crpsp; \\ \propto_{\text{tcr2}} \cdot tcr + \propto_{\text{lcr2}} \cdot lcr + \propto_{\text{csc r2}} \cdot cscr + \propto_{\text{crbf2}} \cdot crbf + \propto_{\text{ccr2}} \cdot ccr; \\ \propto_{\text{lcr3}} \cdot lcr + \propto_{\text{crpsp3}} \cdot crpsp + \propto_{\text{csc r3}} \cdot cscr + \propto_{\text{crbf3}} \cdot crbf + \propto_{\text{ccr3}} \cdot ccr \end{pmatrix} \\ (\propto_{\text{crpsp1}} = 0.2;\ \propto_{\text{tcr1}} = 0.8;\ \propto_{\text{tcr2}} = 0.8;\ \propto_{\text{lcr2}} = 0.08;\ \propto_{\text{csc r2}} = 0.04; \\ \propto_{\text{crbf2}} = 0.04;\ \propto_{\text{ccr2}} = 0.04;\ \propto_{\text{lcr3}} = 0.25;\ \propto_{\text{crpsp3}} = 0.3;\ \propto_{\text{csc r3}} = 0.2;\ \propto_{\text{crbf3}} = 0.1; \\ \propto_{\text{ccr3}} = 0.15), \end{gathered} \tag{7}$$

where $\propto$ denotes weights, and *tcr*, *lcr*, *crpsp*, *cscr*, *crbf*, and *ccr* are the values of transverse cracks, longitudinal cracks, cracks parallel to the slab of the plate, cobweb-like surface cracks, cracks around the balustrade fastener, and corner cracks.

Based on the "Condition Basic Data" and the "Static Calculation," the condition values of the inspections for individual stone plates and the entire side corridor are prepared by the system using fuzzy sets (Table 2). It then determines the condition of the side corridor's plates using the aggregation operators (Table 3).

The logic behind the numbering of stone plates is as follows. The first letter (P) is an abbreviation for stone plate. The second letter indicates the floor on which the side corridor is located (1st-floor side corridor: A; 2nd-floor side corridor: B; 3rd-floor side corridor: C. . .). The next number is the stone plate's serial number on that floor.

The condition assessment assigns two values to the stone plates of the side corridor: firstly, the average condition of the side corridors (A1α), and secondly, the condition of the weakest stone plates (A1β).

The condition of 61 stone plates of side corridors of three residential buildings built in the second half of the 19th century was assessed using the presented method. The results were then compared with the data from the condition assessments conducted by civil engineering experts in the same side corridors. The experts provided a linguistic assessment of both the average condition of the stone plates of the side corridors and the condition of those considered to be the weakest.

The results of the tests are presented in Table 4. For comparative purposes, the table also includes findings from experts' assessments. In sixteen out of the eighteen assessments, the linguistic results from the presented model align with the experts' opinions. With two exceptions, both the experts and the system identified the same stone plate as the weakest.

Table 2. Preparation of the aggregation operators in case of Building 1.

BUILDING 01	Number of stone plates	Edge plate	Reinf.	Vibr. effect	Str.	LBS	Crack inspection						Damage inspection				Exc. insp.	Humidity inspection		Abr. insp.
		EP	RF	VE	ST	ILBS	TCR	LCR	CRPSP	CSCR	CRBF	CCR	DMP	DEP	BE	DBF	EI	SSC	DE	AI
							α_{tcr1} 0.8 α_{tcr2} 0.8	α_{lcr2} 0.08 α_{lcr3} 0.25	α_{crpsp1} 0.2 α_{crpsp3} 0.3	α_{cscr2} 0.04 α_{cscr3} 0.2	α_{crbf2} 0.04 α_{crbf3} 0.1	α_{ccr2} 0.04 α_{ccr3} 0.15	α_{dmp} 0.5	α_{dep} 0.2	α_{be} 0.2	α_{dbf} 0.1		α_{ssc} 0.6	α_{de} 0.4	α_{ai} 0.1
FIRST FLOOR	PA01	1	1	0	0	0.19	0.00	1.00	0.00	0.80	0.57	1.00	0.49	0.90	1.00	0.40	1.00	0.36	0.00	0.85
	PA02	0	0		0	0.21	1.00	1.00	1.00	0.40	1.00	1.00	0.85	0.85	1.00	0.57	1.00			
	PA03	0	1		0	0.23	1.00	0.26	0.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00			
	PA04	0	0		0	0.21	1.00	0.46	0.00	0.20	1.00	1.00	0.90	0.90	1.00	0.90	1.00			
	PA05	0	0		0	0.25	1.00	1.00	0.00	0.40	1.00	1.00	1.00	1.00	0.00	1.00	1.00			
	PA06	0	0		0	1.00	1.00	0.52	1.00	0.90	0.57	1.00	1.00	0.95	0.00	1.00	1.00			
	PA07	1	1		0	0.01	1.00	1.00	0.00	0.80	1.00	1.00	1.00	1.00	0.00	0.40	1.00			
SECOND FLOOR	PB01	1	0	0	0	0.21	1.00	1.00	0.00	0.80	1.00	0.00	0.72	0.90	1.00	0.90	1.00			
	PB02	0	1		0	0.23	1.00	0.34	0.00	0.90	1.00	1.00	1.00	1.00	0.00	0.40	1.00			
	PB03	0	0		0	0.21	1.00	1.00	0.00	0.80	1.00	0.00	1.00	1.00	0.00	1.00	1.00			
	PB04	0	1		0	0.21	0.00	0.46	0.00	0.60	0.57	1.00	0.90	0.90	1.00	0.57	0.80			
	PB05	0	0		0	0.21	1.00	0.32	1.00	0.95	1.00	1.00	0.95	0.95	1.00	1.00	1.00			
	PB06	0	1		0	1.00	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00	0.00	0.57	1.00			
	PB07	1	1		0	0.01	1.00	1.00	0.00	0.40	1.00	0.00	0.90	0.72	0.00	0.20	1.00			

Table 3. Results of the aggregations in case of Building 1.

BUILDING 01	Number of stone plates	Modifiers					Aggregation operators										
		κ_{crk}	κ_{vib}	κ_{lbs}	κ_{rf}	κ_{st}	A1α	A1β	A2α	A2β	A3	A4α	A4γ	A5	A6	A7	A8
									α_{tvtpp} 0.7	α_{hi} 0.2					α_{crk} 0.6	α_{dmg} 0.2	α_{stb} 0.2
FIRST FLOOR	PA01	0.9	0.9	1	0.8	1	0.69	0.57	0.80	0.63	0.22	0.33	0.80	0.19	0.00	0.67	1.00
	PA02	1	1	1	0	1						0.90	0.90	0.21	0.88	0.85	1.00
	PA03	1	1		0.8	1						0.00	0.80	0.23	0.44	1.00	1.00
	PA04	1	1	1	0	1						0.63	0.63	0.21	0.41	0.92	1.00
	PA05	1	1	1	0	1						0.71	0.71	0.25	0.58	0.80	1.00
	PA06	1.1	1	1.1	0	1						0.99	0.99	1.00	0.82	0.79	1.00
	PA07	1	0.9	0	0.8	1						0.00	0.80	0.01	0.66	0.74	1.00
SECOND FLOOR	PB01	1	0.9	1	0	1						0.64	0.64	0.21	0.51	0.83	1.00
	PB02	1	1	1	0.8	1						0.66	0.80	0.23	0.52	0.74	1.00
	PB03	1	1	1	0	1						0.67	0.67	0.21	0.51	0.80	1.00
	PB04	1	1	1	0.8	1						0.34	0.80	0.21	0.00	0.89	0.80
	PB05	1	1	1	0	1						0.89	0.89	0.21	0.82	0.97	1.00
	PB06	1.1	1	1.1	0	1						1.00	1.00	1.00	0.92	0.76	1.00
	PB07	1	0.9	0	0.8	1						0.00	0.80	0.01	0.43	0.61	1.00

Table 4. Experimental results compared to the expert evaluations.

			Expert Evaluation 1	**Expert Evaluation 2**	**Expert Evaluation 3**
Building 1	A1α	0.69	good	good	good
	A1β	0.57	middle rated	middle rated	good
	weakest plate	PA04	PA04	PA04	PB01 (0.58)
Building 2	A1α	0.64	good	good	good
	A1β	0.55	middle rated	middle rated	middle rated
	weakest plate	PA04	PA01 (0.58)	PA04	PA04
Building 3	A1α	0.66	middle rated	good	good
	A1β	0.00	very bad	very bad	very bad
	weakest plate	PA01, PA04, PA05 PA20, PB04, PB05	PB05	PB05	PB05

4. Conclusions

We have developed a framework for a condition assessment and decision support system that is tailored for the objective and uniform examination of old residential buildings and residential building stocks, including the detection and management of errors and anomalies. The system is versatile, allowing for multi-purpose usage. We opted to use fuzzy signatures in the model because they effectively manage uncertainties and data gaps that often arise during condition assessments.

We have named this system the Complex Building's Decision Support System based on Fuzzy Signatures (CBDF system). The results from evaluating the condition of stone plates in the side corridors using the CBDF align consistently with those provided by independent experts.

Given the prevalence of residential buildings with similar structural designs and conditions in Europe's major cities, developing such a condition assessment system is both practical and relevant. As a continuation of our research, our objective is to fully develop all elements of the CBDF system and ultimately present a system that facilitates both the examination and renovation decision support of these buildings.

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