Synthesis and Analysis of Fuzzy Diagnostic Systems for Railway Bridges

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Abstract: - This paper deals with the use of fuzzy logic for building of classification models for the technical condition evaluation of bridge objects, both their superstructure and substructure. The proposed models have hierarchical architecture, built of the Mamdani's fuzzy inference systems. The models were validated on a data set of real bridges in operation. In the modelling process, the analysis of bridge rating methods in the Czech Republic and abroad was applied. The analysis of the number and shapes of input and output membership functions of given fuzzy sets was carried out, and the numbers of fuzzy inference rules were determined. On the basis of the achieved results, the utility of the presented method of soft computing in the evaluation of the bridge technical conditions was proved.

Key-Words: - Bridge condition evaluations; soft computing; fuzzy logic; hierarchical architecture

1 Introduction

Large and long-life structures, such as bridges, suffer by gradual deterioration due to corrosion, fatigue and other processes, and after some time they must be repaired or replaced by a new object. This is very expensive, and such decision must be based on the good knowledge of actual condition.

During long time of railway engineering, various methods have been developed for ensuring safety and sufficient lifetime.

New bridges are usually designed according to codes, e.g. [4,5,6]. Codes are based on theoretical and experimental research and long-time experience. The use of a code guarantees safety for the assumed traffic load, and also sufficient lifetime and safety against premature fatigue failure. This approach is reasonably safe, but also has disadvantages. First, the design is conservative, because various uncertainties exist. The strength and fatigue resistance of individual components or material batches vary. Thus, the design strengths, given in the code, must be so low that there is only a very low probability that the actual strength of any possible component or material of the given brand would be lower. The design is thus often not the most economical. Moreover, also the operation loads vary, more in long-life structures such as bridges, because during long time, new kinds of vehicles can be introduced (often heavier), and there is also tendency to gradual increase of velocities.

There are various ways to improvement, compared to the standard design that uses only the values from material data sheets and the load values given in codes. It is possible to obtain the actual material properties by making strength and fatigue tests of the materials used (also specimens taken from the existing construction can be tested). Also the data about actual load can be obtained by measurement via strain gauges attached to the construction. However, there is always some scatter and uncertainty in these values, because of the limited number of measurements. For this reason, probabilistic methods for safety and lifetime predictions are sometimes used. Nowadays, these methods are mostly based on the Monte Carlo simulation technique [17]. The experience is reasonably good, including the fatigue-life prediction for steel components or constructions [19].

However, the situation with large, complex and long-life structures, such as bridges, is more complicated. In addition to fatigue, there are several other causes of properties degradation, for example corrosion of steel or carbonatation of concrete parts – the effects of which can be enhanced by salts used for deicing. The constructions can also be damaged by frost (freeze-thaw effects), and by wear and other kinds of mechanical action. All these damaging processes can proceed by various velocity at various parts of the structure. Moreover, even if a long-term permanent monitoring of loads would be principially possible today (at the corresponding additional costs), there are many structures, which were put into operation several tens of years ago, and no exact information from their past is available.

Therefore, despite of the existence of various sophisticated methods for the assessment and prediction of fatigue effects accumulation and other damaging processes, inspections of existing bridges, with the observation of their actual state, are indispensable.

Regular inspections of bridges belong to common practice. However, it is impossible to characterise the overall condition of a bridge by a simply measurable quantity. It is influenced by many factors, and many of them can be characterised only verbally (e.g. many short cracks, water seeping into the construction, etc.). As a consequence, the result of evaluation depends to a certain degree on the subjective opinion of the inspector. With respect to the tens of various criteria, it can happen that the evaluation of the same object by two inspectors is less or more different. Therefore, a method is needed, which would be more objective. The probabilistic methods cannot be applied simply in this case, just because of the lack of data and vagueness of the characteristic criteria and way of their evaluation. Fortunately, it appears that the situation can be improved by the application of methods based on modern tools of artificial and computational intelligence, such as fuzzy logic (FL).

The objective of this paper is the reliability and service life of existing bridge objects and their assessment using FL tools. General principles on reliability for various structures are presented in [8]. Bases for design of structures and assessment of existing structures are in [3,9]. From the point of design of new structures and the assessment of existing ones, we are interested in quantification of their reliability level. According to the current level of knowledge and degree of processing of parameters entering the process of structure evaluation, its reliability is quantified using reliability conditions [37]. These conditions are defined in relation to the applied method of reliability theory. According to the way of expressing the random character of reliability parameters, deterministic, semiprobabilistic and fullyprobabilistic methods can be distinguished.

If classical mathematical statistics come from the law of empirical probability, using the knowledge of distribution of probability of random events, the methods for work with uncertainty come from the so-called law of distribution of possibility [28]. The quality of human judgement is characterized by the ability of effective processing of not very precise information. This capability, together with the other qualities of human reasoning, becomes the interest centre of an artificial intelligence (AI) [34]. The AI methods seem to be very promising for the description and control of complicated systems. The most important of them are the possibility of processing non-numerical, linguistic information. Approaches of modelling, where this integration of knowledge is enabled, the ability of self-learning, robustness and easy implementation are supported at the expense of preciseness, and they are ranged into the framework of the so called “soft computing“ or “computational intelligence” [16,23,27,28,30].

The goal of this paper is a verification of the use of FL for the evaluation of the technical conditions of existing bridge objects, thereby also their reliability and service life, on the bases of models of their defects (damages).

2 Problem Formulation

Within the 6th Framework programme of the European Union, an international research project on sustainable bridge operation has been solved [38]. The rules for carrying out inspections and condition assessments of existing railway bridges are presented in [35], and in [36] for load determining and resistance assessment of railway bridges.

Available results of [35,36,38] have been adopted into this research, it means methodology of hierarchical classification of railway bridge defects, application of non-dimensional geometrical bridge model, the way of quantitative defects description and principles for initial assessment (rating) level of bridge condition.

The basic characteristic of reliability of an existing bridge is its load-carrying capacity, regarding its actual technical condition and representing also the basic quantitative parameters. Data obtained during inspection and condition assessment are crucial to estimate the current state of bridge structure reliability. Thus, the basis of reliability assessment of the bridge is the evaluation of its condition, which in practical judging data is, however, often incomplete, numerically imprecise and also linguistic.

A supervising activity in [39] consists of general (annual) and detailed (three yearly) inspections namely. The protocol about a detailed bridge inspection quotes the found faults and the proposal of total condition classification of the railway bridge object using three degrees [39]. Degree 1 – condition state “good” means that bridge object requires only general maintenance. Degree 2 – “satisfactory” means that bridge object requires repair extending the general maintenance framework, and replacement of some parts if necessary, however the defects do not immediately threaten the safety of operation. Degree 3 – “unsatisfactory” means that the bridge object requires full reconstruction, reconstruction of supports or the replacement of superstructure, and if necessary, even only the repair or replacement of some parts, whose condition do not immediately threaten the safety of operation. The condition evaluation of bridge superstructure and substructure is always recorded separately.

At this place, it should be noted that various kinds of bridge-safety classification are used in various countries. For example, the above described 3-degree scale is common for railways in the Czech Republic. Slovak railways use a 5-degree scale (1 – perfect, 2 – good, 3 – satisfactory, 4 – bad, 5 – emergency). Czech roads and highways directorate uses a 7-degree scale (1 – excellent, 2 – very good, 3 – good, 4 – satisfactory, 5 – bad, 6 – very bad, 7 – emergency). Polish railway bridges are classified using a continuous scale between degree 5.0 (excellent) and 0.0 (emergency). The systems with more degrees enable better distinguishing of the actual state. The new FL diagnostic system, described in the following text, has been tested on actual bridges by comparing the "fuzzy-based" results with those done by experts working with the 3-degree classification. Nevertheless, one shall see that also in this case the proposed fuzzy diagnostic system enables finer and more precise characterisation.

In this work we have chosen twelve real bridges (of the given construction type) with various proposed condition evaluation of their superstructure and substructure, done by inspectors. Then, the data could be evaluated about defects found from the protocols about their detailed inspections. Afterwards, we described these defects quantitatively according to the principles given in [35]. The condition of bridge superstructure and substructure is always evaluated on the basis of the found defects [39]. Bridge defects are hierarchically classified [35] in four levels. In the highest level, there are defects classified into six types: 1st means "contamination", 2nd "deformation", 3rd "deterioration", 4th "discontinuity", 5th "displacement" and the last is "loss of material". In the lower level, each defect type has more defect kinds, e.g. 6.1 for "loss of concrete" and 6.2 "loss of steel" for "loss of material". In the other of the remaining levels, the defect kinds have categories and these then can have defect classes [20,32,33,37].

Furthermore, the bridge defects d_i are described as a triple by their parameters: defect extent e_i, defect intensity i_i and defect location by the following way:

$$d_i = \{ \textit{defect location}, e_i, i_i \}, \qquad (1)$$

where: *defect location* means superstructure or substructure of the bridge, and e_i and i_i are defined for defect types of the bridge.

3 Fuzzy diagnostic model

This section is focused on the design of a diagnostic model for bridge defect evaluation. This model is possible perceived classification problem. Classification deals with knowledge and data characterized by uncertainty. This was realized by means of a fuzzy inference system (FIS) [15,30]. The heuristic approach for the creation of FIS (it means the shape and number of membership function (MF) for input and output variables, and the fuzzy rule base) was used because an exact general method for definition of their number does not exist [16,31]. A definition of the number of fuzzy rules is described in [15,16,31,43,44,45,46], or the method in [13,22,42] can be used. The number of fuzzy rules can also be optimized by genetic algorithms and evolution strategies [1,25].

The FIS is (Fig.1) represented by a block with inputs in_n and output *out* and can be defined as MISO (Multiple Inputs and Single Output) system. It is more described in [16,29,23,24].

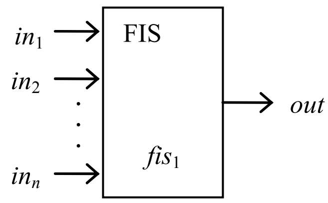

Fig.1 MISO fuzzy inference system

The general structure of FIS is presented in Fig.2 [13,23]. It contains processes of fuzzification, inference and defuzzification. Inputs of FIS are crisp values, and its output is the crisp value, too.

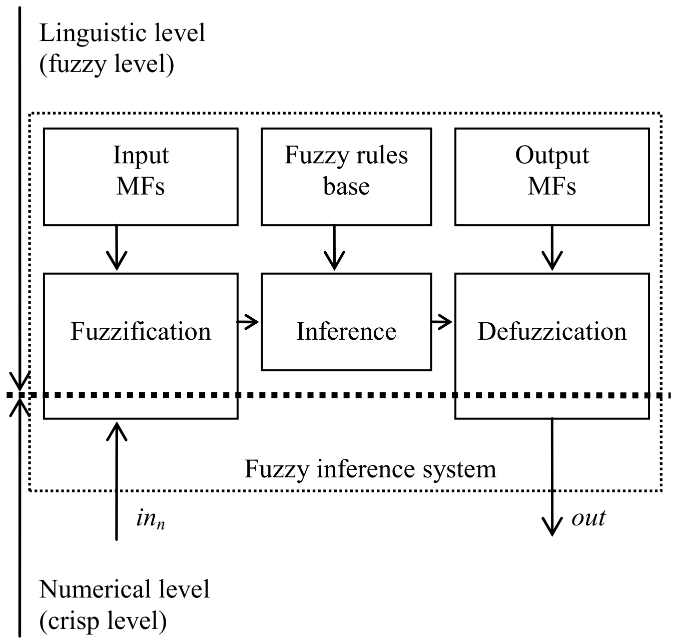

Fig.2 General structure of FIS

Normalisation of the inputs in_n and their transformation to the range of values of the input MFs (it means to degrees of MFs of fuzzy sets) is realised during the fuzzification process. The inference mechanism is based on the operations of FL (min and max) and implication within fuzzy rules from the fuzzy rule base [18,19,24,30]. Transformation of the outputs of individual rules to the output fuzzy set is realised on the basis of the aggregation process [24,30]. Conversion of fuzzy values to expected crisp value *out* is realised during the defuzzification process. The most commonly-used defuzzification method is the Centre of Gravity method, one of the simplest defuzzification methods is the Max Criterion Method, eventually the Mean of Maxima Method. A universal method for designing shape, the number and parameters of the input and output MFs do not exists. Triangular, trapezoidal and other MFs are used for the design of FIS. In the Mamdani's FIS the fuzzy rule r_n can be written as follows [23,24]:

$$r_n : \text{IF } in_1 \text{ is } A \text{ AND } in_2 \text{ is } B \text{ AND } \dots \text{ AND } in_n \text{ is } C \text{ THEN } out \text{ is } D, \quad (2)$$

where: A, B, C and D represent fuzzy sets of inputs and output linguistic variables.

A disadvantage of MISO approach (it means the using only a FIS) to the design of FIS [7,12,14,27,29,] is an exponential growth of the number of fuzzy rules in the fuzzy rule base, and the FIS can be realized ineffectively and an explanation cannot be perspicuous.

This problem can be removed by a hierarchical structure (Fig.3) of FIS [7,14,27,29]. In the hierarchical structure of FIS it is necessary to determine the number of fuzzy rules for the first and other levels, see more in [29].

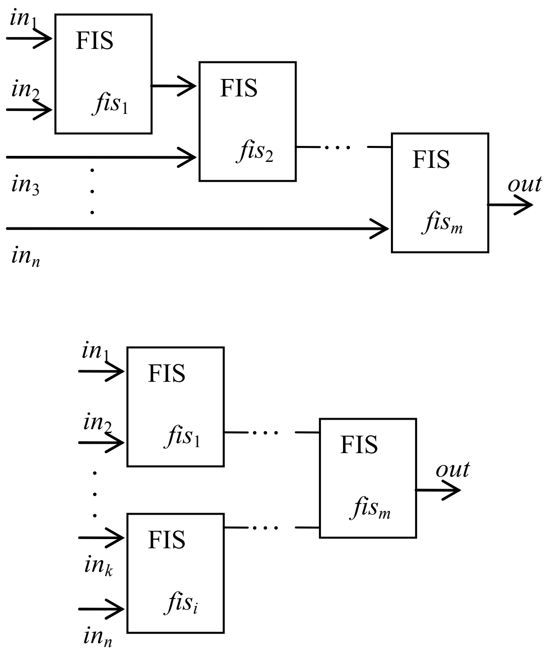

Fig.3 Types of FIS hierarchical structure

The following parts are focused on the design of hierarchical fuzzy diagnostic models (HFDMs). This problem is composed of two phases: the first one is a synthesis and analysis of $HFDM_1$ for evaluation of bridge superstructure defects and the second one is a synthesis and analysis of $HFDM_2$ for the evaluation of bridge substructure defects. Parameters for HFDMs can be characterized by incompleteness, uncertainty, and disproportion. HFDMs are created in MATLAB.

3.1 Fuzzy diagnostic model of bridge superstructure

The superstructure of the chosen constructional type of bridge has two main structural materials – both steel and concrete. Therefore, in this case, at least in three (i.e. half) of the defect types, which have a bigger impact (weight) on the resulting condition index. In the following Fig.4, the fuzzy diagnostic model for evaluation of bridge superstructure defects $HFDM_1$, utilised for the evaluation of the technical condition of the massive steel-concrete bridge superstructure, on the basis of its found defects, which are classified and described according to the guideline [35], is shown.

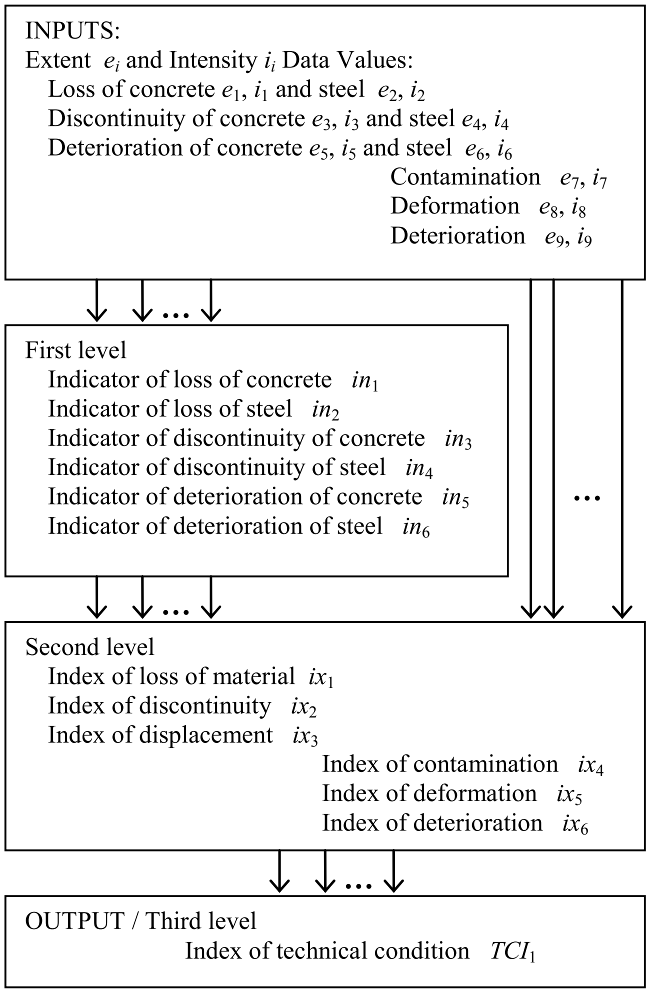

Fig.4 Fuzzy diagnostic model for evaluation of bridge superstructure defects

Proposed $HFDM_1$ represent three-level hierarchical structure in Fig.5. Inputs level represents the set of real inputs $\{e_1, i_1, e_2, \dots, e_9, i_9\}$. There are: input 1 ($e_1$, i_1) correspond to extent and intensity of loss of concrete, input 2 (e_2, i_2) is means extent and intensity of loss of steel, input 3 (e_3, i_3) is extent and intensity of discontinuity of concrete, input 4 (e_4, i_4) is extent and intensity of discontinuity of steel, input 5 (e_5, i_5) is extent and intensity of deterioration of concrete, and input 6 (e_6, i_6) is extent and intensity of deterioration of steel.

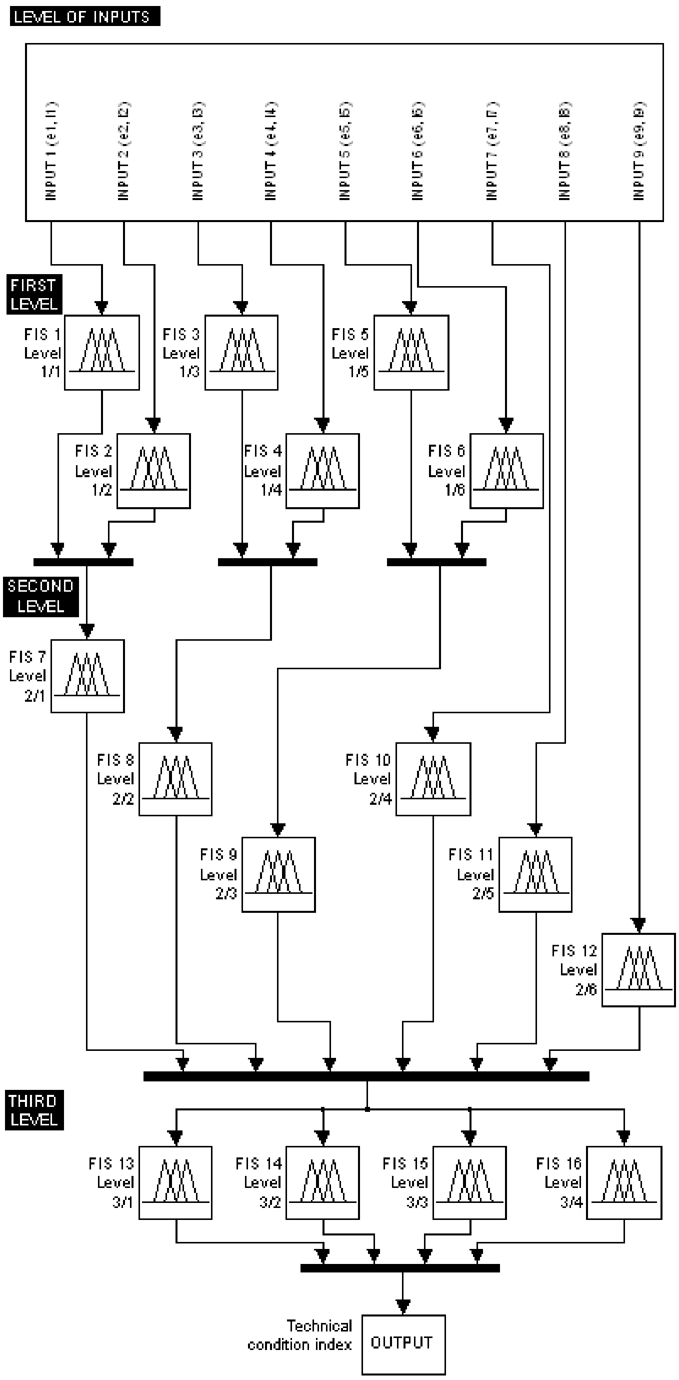

Fig.5 Proposed $HFDM_1$ in MATLAB

The first level (defect kinds level) is created by 6 Mamdani's FISs $\{FIS_1$ (Level 1/1), FIS_2 (Level 1/2), …, FIS_6 (Level 1/6)$\}$ and represents the evaluation of indicators of (some) defect kinds of bridge superstructure $\{in_1, in_2, \dots, in_6\}$. FIS_1 has two inputs e_1, i_1 and output in_1; FIS_2 has two inputs e_2, i_2 and output in_2 etc. Every FISs have 3 input and output MFs and 9 fuzzy rules.

The second level (defect type level) is created by 6 Mamdani's FISs $\{FIS_7$ (Level 2/1), FIS_8 (Level 2/2), …, FIS_{12} (Level 2/6)$\}$ and represents the evaluation of indices of (all) defect types of bridge superstructure $\{ix_1, ix_2, \dots, ix_6\}$. FIS_7 has two inputs in_1, in_2 and output ix_1; FIS_8 has two inputs in_3, in_4 and output ix_2; FIS_9 has two inputs in_5, in_6 and output ix_3; FIS_{10} has two inputs e_7, i_7 and output ix_4; FIS_{11} has two inputs e_8, i_8 and output in_5 and FIS_{12} has two inputs e_9, i_9 and output ix_6. Every FISs have 3 input and output MFs and 9 fuzzy rules.

The third level (technical condition level) is created by 4 Mamdani's FISs $\{FIS_{13}$ (Level 3/1), FIS_{14} (Level 3/2), …, FIS_{16} (Level 3/4)$\}$ and represents the evaluation of the (one) index of the technical condition of bridge superstructure TCI_1. Every FISs have six inputs $\{ix_1, ix_2, \dots, ix_6\}$ and output TCI_1. FIS_{13} has 3 MFs of TCI_1, FIS_{14} has 5 MFs of TCI_1, FIS_{15} has 7 MFs of TCI_1 and FIS_{16} has 9 MFs of TCI_1. Every FISs have 3 input MFs and 729 fuzzy rules. The output variable TCI_1 has values from 1.00 to 3.00.

In a choice of the input and output MFs, a comparison of Gaussian membership functions of the first type with (starting) triangular membership functions was carried out. The Mean of Maxima method was chosen for the defuzzification.

In the following Tables 1 to 3 the value ranges (scale of universe) of inputs for FISs in all three $HFDM_1$ levels are presented.

Table 1 Value ranges of inputs for FISs in the first level of $HFDM_1$

Kind of defect	Extent of defect kind		Intensity of defect kind	
	Min.	Max.	Min.	Max.
Deterioration of concrete	0	100	0	40
Deterioration of steel	0	100	0	20
Discontinuity of concrete	0	100	0	20
Discontinuity of steel	0	100	0	20
Loss of concrete	0	100	0	40
Loss of steel	0	100	0	20

Note: All values are in percents, only the intensity of discontinuity of concrete is in millimeters.

Table 2 Value ranges of inputs for FISs in the second level of $HFDM_1$

Type of defect	Indicator of defect kind of concrete		Indicator of defect kind of steel	
	Min.	Max.	Min.	Max.
Deterioration	0.00	1.00	0.00	1.00
Discontinuity	0.00	1.00	0.00	1.00
Loss of material	0.00	1.00	0.00	1.00

Note: All values are non-dimensional.

Type of defect	Extent of defect type		Intensity of defect type	
	Min.	Max.	Min.	Max.
Contamination	0	100	0	100
Deformation	0	100	0	100
Displacement	0	100	0	100

Note: All values are in percents.

Table 3 Value ranges of inputs for FISs in the third level of $HFDM_1$

Type of defect	Index of defect type	
	Min.	Max.
Contamination	0.00	1.00
Deformation	0.00	1.00
Deterioration	0.00	1.00
Discontinuity	0.00	1.00
Displacement	0.00	1.00
Loss of material	0.00	1.00

Note: All values are non-dimensional.

Verification of $HFDM_1$ of the condition evaluation of bridge superstructure was carried out by means of testing values in each of the sixth of the range of values (universum, scale). In the following Tables 4 to 6 the testing values of the input and output parameters for FISs in all three $HFDM_1$ levels are presented.

3.2 Fuzzy diagnostic model of bridge substructure

The substructure of the chosen constructional type of bridge has only one main structural material – either concrete or stone. Therefore, in this case, in none of the defect types we created another level of the model, introducing for these defects types also defect kinds. In the following Fig.6, the fuzzy diagnostic model for evaluation of bridge substructure defects $HFDM_2$, utilised for the evaluation of the technical condition of the massive concrete or stone bridge substructure, on the basis of its found defects, which are classified and described according to the guideline [35], is shown. Models ($HFDM_2$ and $HFDM_1$) are very much alike.

Proposed $HFDM_2$ represent two-level hierarchical structure. Inputs level represents the set of real inputs $\{e_{10}, i_{10}, e_{11}, \ldots, e_{15}, i_{15}\}$. There are: input 1 ($e_{10}$, i_{10}) correspond to extent and intensity of loss of material, input 2 (e_{11}, i_{11}) is means extent and intensity of discontinuity, input 3 (e_{12}, i_{12}) is extent and intensity of deterioration, input 4 (e_{13}, i_{13}) is extent and intensity of contamination, input 5 (e_{14}, i_{14}) is extent and intensity of deformation, and input 6 (e_{15}, i_{15}) is extent and intensity of diplacement.

Table 4 Testing values of the input and output defect kind parameters of $HFDM_1$

Input/ output	Part of scale						
	0/6	1/6	2/6	3/6	4/6	5/6	6/6
e_5	0	17	33	50	67	83	100
i_5	0	7	13	20	27	33	40
in_5	0.025	0.085	0.5	0.5	0.5	0.915	0.975
e_6	0	17	33	50	67	83	100
i_6	0	3	7	10	13	17	20
in_6	0.025	0.085	0.495	0.5	0.495	0.915	0.975
e_3	0	17	33	50	67	83	100
i_3	0	3	7	10	13	17	20
in_3	0.025	0.085	0.495	0.5	0.495	0.915	0.975
e_4	0	17	33	50	67	83	100
i_4	0	3	7	10	13	17	20
in_4	0.025	0.085	0.495	0.5	0.495	0.915	0.975
e_1	0	17	33	50	67	83	100
i_1	0	7	13	20	27	33	40
in_4	0.025	0.085	0.5	0.5	0.5	0.915	0.975
e_2	0	17	33	50	67	83	100
i_2	0	3	7	10	13	17	20
in_2	0.025	0.085	0.495	0.5	0.495	0.915	0.975

Note: All values e_i and i_i are in percents, values i_4 are in millimeters, and values in_i are non-dimensional.

Table 5 Testing values of the input and output defect type parameters of $HFDM_1$

Input/ output	Part of scale						
	0/6	1/6	2/6	3/6	4/6	5/6	6/6
e_7	0	17	33	50	67	83	100
i_7	0	17	33	50	67	83	100
ix_4	0.025	0.085	0.495	0.5	0.495	0.915	0.975
e_8	0	17	33	50	67	83	100
i_8	0	17	33	50	67	83	100
ix_5	0.025	0.085	0.495	0.5	0.495	0.915	0.975
in_5	0.025	0.085	0.5	0.5	0.5	0.915	0.975
in_6	0.025	0.085	0.495	0.5	0.495	0.915	0.975
ix_3	0.025	0.04	0.5	0.5	0.5	0.96	0.975
in_3	0.025	0.085	0.495	0.5	0.495	0.915	0.975
in_4	0.025	0.085	0.495	0.5	0.495	0.915	0.975
ix_2	0.025	0.04	0.5	0.5	0.5	0.96	0.975
e_9	0	17	33	50	67	83	100
i_9	0	17	33	50	67	83	100
ix_6	0.025	0.085	0.495	0.5	0.495	0.915	0.975
in_1	0.025	0.085	0.5	0.5	0.5	0.915	0.975
in_2	0	3	7	10	13	17	20
ix_1	0.025	0.04	0.5	0.5	0.5	0.96	0.975

Note: All values e_i and i_i are in percents, all other values in_i and ix_i are non-dimensional.

Table 6 Testing values of the input and output technical condition parameters of $HFDM_1$

Input/ output	Part of scale						
	0/6	1/6	2/6	3/6	4/6	5/6	6/6
ix_4	0.025	0.085	0.495	0.5	0.495	0.915	0.975
ix_5	0.025	0.085	0.495	0.5	0.495	0.915	0.975
ix_3	0.025	0.04	0.5	0.5	0.5	0.96	0.975
ix_2	0.025	0.04	0.5	0.5	0.5	0.96	0.975
ix_6	0.025	0.085	0.495	0.5	0.495	0.915	0.975
ix_1	0.025	0.04	0.5	0.5	0.5	0.96	0.975
ix_7 (3MFs)	1.05	1.08	2	2	2	2.92	2.95
ix_7 (5MFs)	1.02	1.04	2	2	2	2.96	2.98
ix_7 (7MFs)	1.02	1.02	2	2	2	2.98	2.98
ix_7 (9MFs)	1.02	1.02	2	2	2	2.98	2.98

Note: All values ix_i are non-dimensional.

The first level (defect type level) is created by 6 Mamdani's FISs {FIS_{17} (Level 1a/1), FIS_{18} (Level 1a/2), …, FIS_{22} (Level 1a/6)} and represents the evaluation of indices of (all) defect types of bridge substructure {jx_1, jx_2, …, jx_6}. FIS_{17} has two inputs e_{11}, i_{11} and output jx_1; FIS_{18} has two inputs e_{12}, i_{12} and output jx_2 etc. Every FISs have 3 input and output MFs and 9 fuzzy rules. The second level (technical condition level) is created by 4 Mamdani's FISs {FIS_{23} (Level 2a/1), FIS_{24} (Level 2a/2), …, FIS_{26} (Level 2a/4)} and represents the evaluation of the (one) index of the technical condition of bridge substructure TCI_2. Every FISs have six inputs {jx_1, jx_2, …, jx_6} and output TCI_2. FIS_{23} has 3 MFs of TCI_2, FIS_{24} has 5 MFs of TCI_2, FIS_{25} has 7 MFs of TCI_2 and FIS_{26} has 9 MFs of TCI_2. Every FISs have 3 input MFs and 729 fuzzy rules. Gaussian first type of inputs and output MFs and Mean of Maxima defuzzification method were used.

In the following Table 7 the value ranges (scale of universe) of inputs for FISs in $HFDM_2$ are presented.

Table 7 Value ranges of inputs for FISs in the first level of $HFDM_2$

Kind of defect	Extent of defect kind		Intensity of defect kind	
	Min.	Max.	Min.	Max.
Loss of material	0	100	0	40
Discontinuity	0	100	0	20
Deterioration	0	100	0	40
Contamination	0	100	0	100
Deformation	0	100	0	100
Displacement	0	100	0	100

Note: All values are in percents, only the intensity of discontinuity is in millimeters.

Values of input variables of indexes {jx_1, jx_2, …, jx_6} for the second level of $HFDM_2$ are from 0.00 to 1.00. The output variable TCI_2 has values from 1.00 to 3.00.

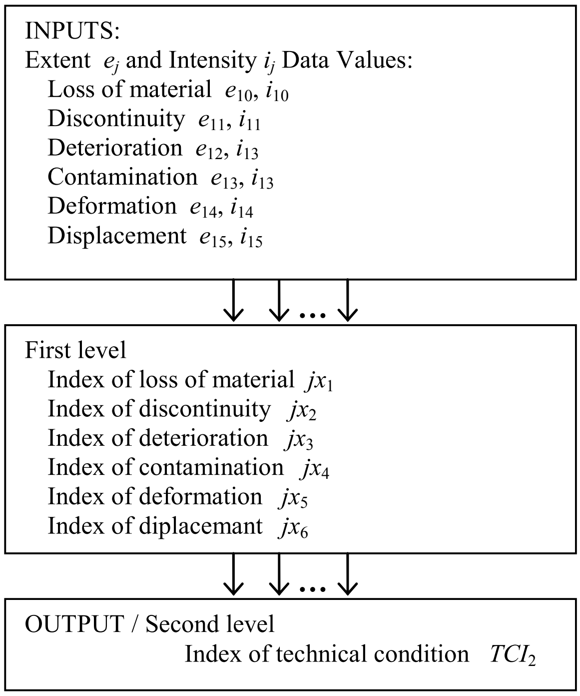

Fig.6 Fuzzy diagnostic model for evaluation of bridge substructure defects

Verification of $HFDM_2$ of the condition evaluation of bridge substructure was carried out by means of testing values like the verification of $HFDM_1$.

3.3 Validation of fuzzy diagnostic models

After verification, it is necessary to adjust parameters of simulation models ($HFDM_1$ and $HFDM_2$) into the process of validation (whether the simulator reflects the object of examination with the required accuracy, which is expected from it and which was given in the initial targets) [32]. The validation can be ascertained by various methods, for example; to compare the model with a real system by means of statistical methods, or empirically, when an independent expert verifies the veracity of the model's behaviour.

For the validation twelve bridges real data of the protocol about a detailed bridge inspection with the proposal of the technical condition evaluation of both bridge superstructure and substructure was used.

The bridge [33] was described by {bridge object, track section, name of the track, evidence km, proposal of evaluation, established name, local RIA} for example Bridge No. 1 = {bridge object -01, track section - 0101, name of the track - Praha-Bubny – Chomutov záp. zhl., evidence km – 5.141, proposal of evaluation - 3 / 2, established name - Praha, ul. Spojovací, local RIA - Praha }, and Bridge No. 3 = {bridge object - 04, track section - 0101, name of the track - Praha-Bubny – Chomutov záp. zhl., evidence km – 21.218, proposal of evaluation - 2 / 1, established name - Pavlov, local RIA - Praha }, etc.

WE used the inputs validation data from [33] (see more Table 2 and Table 6 in [33]) for evaluations of the technical condition index of bridge superstructure and substruction. Results are presented in Table 8.

Table 8 Values of bridge evaluation for superstructure and substruction

Bridge No.	$HFDM_1$			$HFDM_2$		
	TCI_1		Expert value	TCI_2		Expert value
	3 MFs	9 MFs		3 MFs	9 MFs	
1	2	1.75	2	1.08	1.25	1
2	2	2	2	1.08	1.02	1
3	2	2	2	1.08	1.25	2
4	2	1.75	2	1.08	1.5	2
5	2	2	2	2	2	2
6	2	2	2	2	1.75	2
7	2	2	3	2.92	2.5	3
8	2	2	3	2.92	2.75	3
9	2	2	3	2	1.75	3
10	2.92	2.5	3	2	2.25	3
11	2	2	3	2	2.25	3
12	2	2	3	2.92	2.5	3

4 Conclusion

We have presented the synthesis and analysis of models for the condition evaluation of railway bridges by one of the methods of soft computing. The proposed method of evaluation of technical condition of existing bridges using FL is interesting and effective. At the same time the paper concentrates on practical application and indicates the way this system can proceed in its development.

The work has proven the utility of FL for the evaluation of bridge technical conditions. To further facilitate the use of this method, we propose that the data of bridge technical condition should be collected in a more appropriate manner by means of the proposed inspection forms.

It is possible to state, as shown above, that the best result is achieved by the simulation model, created using FIS with nine output membership functions TCI_1 and TCI_2 (9 MFs). It is because of the fact that the bigger amount of membership functions of the output variable expresses the resulting assessment of the bridge technical condition more exactly and with more details.

Using the resulting values concerning the technical condition of individual bridges with values 1, 2, 3, realistic approximate values (e.g. 2.25) are obtained. Managerial decision-makers would then be able to make use of this technical condition index data and as such they would be able to prioritise funding regarding the repair of bridge structures (e.g. 2.75 needing repair more than 2.25).

The obtained knowledge will be used in further research in the given branch. On the basis of analysis of the simulation model it would be possible to optimise the number and shapes of input and output membership functions by means of genetic algorithms [22,28], and also to optimise the number of rules in FIS by means of the so-called theory of rough sets [2,10,11,26]. It is possible to use artificial neural networks [40], fuzzy cognitive maps [41], and neuro-fuzzy model.

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