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Multicriterial Condition Evaluation and Fuzzy Methods

Jaroslav Menčík

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Abstract

This chapter describes various methods for reduction of uncertainties in the determination of characteristic values of random quantities (quantiles of normal and Weibull distribution, tolerance limits, linearly correlated data, interference method, Monte Carlo method, bootstrap method).

Keywords: Random quantity, uncertainty, normal distribution, Weibull distribution, tolerance limits, correlation, interference method, Monte Carlo method, bootstrap method

Large and long-life engineering structures, such as bridges, dams, buildings, or cooling towers, deteriorate gradually due to corrosion, mechanical damage, fatigue, and other processes. As a consequence, their safety slowly decreases, and after some time, they must be repaired. Every decision of a repair must be based on a good knowledge of the actual technical condition. This is gained from regular inspections. However, it is impossible to characterize the overall condition of a complex object by means of only one simply measurable quantity. It is influenced by many factors, and most of them can be characterized only verbally (e.g. slightly corroded reinforcement or many short cracks in the wall). Probabilistic and exact methods cannot be applied everywhere, often because of the lack of data and the vagueness of the characteristic criteria and way of their evaluation, and also because of the lack of appropriate models relating the extent of the defects to the load-carrying capacity or lifetime of the object. The overall safety and reliability characteristic is obtained by a suitable processing of many partial ratings, each for every criterion. Such evaluation is usually based on a judgement by a person with long practice – an expert. The results of this approach, using his experience and intuition, are usually reasonably good. Nevertheless, methods that are more objective and less sensitive on the person of the inspector are needed. In this chapter, two procedures will be described: a simple method that assigns weights to the individual criteria and uses a simple rule for their aggregation, and an advanced method for more complex cases, which uses fuzzy logic tools.

Simple multicriterial condition assessment

The method can be explained on the evaluation of bridges, but a similar approach may be used for other objects, too. The decision on a repair is based on the results of inspections. Various systems exist for the classification of bridge condition, usually based on a scale with several degrees. For example, in Czech Republic a three-degree scale is used for railway bridges (1 = good, 2 = satisfactory, 3 = unsatisfactory), whereas a seven-degree scale is used for road bridges (1 = faultless, 2 = very good, 3 = good, 4 = satisfactory, 5 = bad, 6 = very bad, 7 = emergency, danger of collapse). In Poland, a continuous scale between 0 and 5 is used.

The condition evaluation is based on several criteria. For small concrete railway bridges, they pertain to: 1 = condition of the beams, 2 = condition of water insulation, 3 = condition of the cornice, and 4 = response to train passage. The bridge inspection protocol with verbal description of the situation serves for assigning weights to the individual criteria. This is facilitated by the catalog relating the weights to various degree of damage. The sum of the weights for individual criteria forms the resultant characteristic of the overall condition (R) and serves for the decision whether or not the bridge should be repaired.

The procedure will be explained here on an example of a simple bridge [1].

Example 1

A concrete bridge was inspected to evaluate its overall condition. The results of the inspection, written into a protocol, were as follows:

1. Concrete beams. The concrete plastering between the beams at the bridge bottom is with cracks, the steel beams have begun corroding.
2. Water insulation. The insulation is damaged, the slab and supports leak water through, lime leaches are formed.
3. Cornice. Hair cracks exist along the height on the left side, the lower edge above the support no. 2 has fallen away, the reinforcement is bare.
4. Response during train passage. Quiet.

These results were then compared with the catalog of weights (W) for various conditions. An extract from the list is shown below. The first subscript denotes the criterion and the second subscript denotes the classification. The weights range from 0 to 1; higher values correspond to better condition.

1. **Concrete beams** (7-degree classification). $W_{1,7} = 0.9 - 1.0$: Concrete plastering is without cracks, the steel reinforcement is fully covered, the edges of beams are without rust, protective painting is in order. $W_{1,6} = 0.8$: Concrete plastering at the bottom contains hair cracks, the steel reinforcement is bare at lengths less than 0.05 m (i.e. not substantial), the edges of beams are with slight rust, the protective painting starts flaking off. $W_{1,1} = 0.0 - 0.1$: The plastering has significantly fallen away, the edges of steel beams are very rusty, with the thickness reduced by 2 to 3 mm, cracks are present in the concrete, and the concrete crumbles up to the depth 60 mm.

2. **Water insulation** (5 degrees). $W_{2,5} = 1.0$: Good, water seepage not found. $W_{2,1} = 0.0 - 0.3$: Heavily damaged, intensive seeping over the total area, lime stalactites have been formed.
3. **Cornice** (5 degrees). $W_{3,5} = 1.0$: Concrete plastering is without cracks, the steel reinforcement is fully covered, the edges of beams are without rust, protective painting is in order. $W_{3,1} = 0.0 - 0.3$: The plastering has significantly blown and fallen away, the edges of steel beams are heavily rusty and with the thickness reduced by 2 to 3 mm, cracks appear in the concrete, the concrete crumbles up to the depth 60 mm.
4. **Response during train passage** (3 degrees). $W_{4,3} = 0.8 - 1.0$: Quiet. $W_{4,2} = 0.5 - 0.7$: Neither quiet nor unsteady. $W_{4,1} = 0.0 - 0.4$: Unsteady.

Based on this list, the individual criteria of the investigated bridge were assigned the following weights: $W_1 = 0.65$, $W_2 = 0.45$, $W_3 = 0.85$, and $W_4 = 0.90$. The resultant characteristic R of the overall condition is obtained as the sum of the individual weights:

$$R = W_1 + W_2 + W_3 + W_4 = 0.65 + 0.45 + 0.85 + 0.90 = 2.85.$$

This result can be interpreted using the following 3-degree scale based on experience:

$R = 3.0 - 4.0$, Degree 1. Condition: Good. Load-carrying construction needs only common maintenance.

$R = 1.8 - 3.0$, Degree 2. Condition: Satisfactory. Load-carrying construction needs repair (more extensive than common maintenance), but the defects do not endanger the safety.

$R = 0.0 - 1.8$, Degree 3. Condition: Unsatisfactory. Load-carrying construction needs total reconstruction or exchange of the load-carrying construction or substantial repair.

The above value $R = 2.85$ can thus be interpreted as "satisfactory condition, but a repair is necessary". The bridge manager will decide about the repair (also with respect to the money available, condition of other bridges in the network, etc.; see Chapter 17).

Note: The method can be improved by assigning weights to the groups of individual criteria to better respect the influence of each criterion on the safety of the whole structure.

2. Fuzzy logic approach to condition assessment

As we have seen, the above characterization of bridge condition was based not on exact values but on rather vague terms. There are many situations like this. In daily life, we often describe the situation as "slightly increased temperature" or "the girders are very rusty". Even a driver controls his car in terms "fast-slow" and "near-far". The necessity of working with such "fuzzy" quantities has led to the development of methods based on fuzzy sets [2, 3]. These methods enable work with linguistic and numerical quantities and allow their combination as well as the use of mathematical and logical operators (IF, AND, OR, THEN,...). The procedures for application of fuzzy methods are principally similar as the above multicriterial condition assessment. However, instead of one single ("sharp") value for each criterion, they use so-

called membership functions and offer more flexibility and better characterization of the situation (Figure 1A). The application of fuzzy logic on decision processes consists of three steps: fuzzification, fuzzy inference, and defuzzification.

STEP 1. Fuzzification

The real values of input variables are transformed into fuzzy values of linguistic variables. This is done by assigning a suitable attribute to each basic variable. An example of such variable is "deflection of a beam" and an example of an attribute is "small". Often, three to seven attributes are used (e.g. positive big, positive medium, positive small, zero, negative small, negative medium, and negative big). The fuzzy approach uses membership functions that express the degree of correspondence of individual quantities to their definitions. For example, usual operating temperature of a machine is from 40°C to 70°C. The temperature 75°C can be considered as increased, but still also as operating. Its appropriateness to operating conditions, however, is not so high as if it were within the above interval. The fuzzy approach enables dealing with just such cases. Examples of various membership functions are shown in Figure 1A; $\mu(x) = 1$ means full correspondence of x with its definition.

STEP 2. Fuzzy inference

In the second step, mathematical and logic operations are performed with the fuzzified input variables. For example, "If 'A' is small and 'B' is high, then 'C' is small". The output is also fuzzy or in a form of a linguistic variable. A suitable processing of membership functions for several input variables gives the membership function of the result. For example, if a load "about 5 kN" acts on a structure and also a load "about 10 kN", then the total load is "about 15 kN". Figure 1B shows this simple case for triangular membership functions.

STEP 3. Defuzzification

In this step, the fuzzy result is transformed into a sharp value of the output variable, characterizing the overall condition, e.g. "the damage degree is 4.3". Various methods exist for this purpose: position of the centroid of the resultant membership function, the first of maxima, etc. If the technical condition of a structure is evaluated, the resultant statement can be "the condition is good (satisfactory, bad,...)". This serves for the decision about the further operation or repair of the object.

Figure 1. (A) Examples of membership functions and (B) example of composition of two fuzzy quantities ($F = F_1 + F_2$).

The condition assessment using fuzzy logic needs computer support. Special programs may be created, but commercial software can also be used. For example, Matlab offers universal Fuzzy Logic Toolbox [4]. It enables the definition of various membership functions (e.g. for the intensity of damage and extent of damage or other quantities relevant to the particular problem). The user can also choose the rules for the inference process from a database. The solution is controlled by the editor of fuzzy inference system (Fig. 2), and the results can be presented in graphic form.

Figure 2. Editor of fuzzy inference system in Matlab®.

The main parts of a fuzzy-logic tool are: an editor, databases of membership functions and rules for work with them, and a viewer on the resultant membership function. Before computer-aided condition evaluation with fuzzy methods may be applied on an engineering object, the following steps must be done:

1. Definition of quantities, which have influence on the condition of the object.
2. Definition of membership functions for individual attributes of each quantity.
3. Definition of rules for the construction of the resultant membership function.
4. Definition of rules for defuzzification (= for assigning a sharp value to the characteristic quantity), allowing unambiguous decision about operation or repair.

There are many publications on fuzzy methods. Their use for reliability assessment is explained in [2, 3, 5 - 7]. Rudolf [8] developed an application of computer aided fuzzy inference for the evaluation of bridges; see also [1].

Author details

Jaroslav Menčík

Address all correspondence to: jaroslav.mencik@upce.cz

Department of Mechanics, Materials and Machine Parts, Jan Perner Transport Faculty,
University of Pardubice, Czech Republic

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