Fuzzy logic techniques in bridge management systems

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Abstract: Bridge-management systems are suggesting the required repair-work algorithmically. Sufficiency is derived from "IF-THEN" type logic decisions, or in more sophisticated applications as a group of parametric decisions.

The contradiction between the "crisp" nature of algorithmically definable standards, and "soft" technical benchmarks derived from professional practice can be resolved by the introduction of "fuzzy logic" to the particular field. Applying *fuzzy logic* the compliance conditions/measures are not crisp values, but defined by fuzzy membership functions.

The complex sufficiency index of bridges incorporating the load bearing-; width-; and clear height sufficiency are given on a 100 grade scale with 10 categories.

The connecting element between the input (load bearing – width – clear height sufficiency data) and the output (complex sufficiency ratings) is the rules of logical preconditions based on the professional knowledge. For every combination of input ratings the rules designate separate complex sufficiency ratings.

For executing the fuzzy deductions, in this paper the Mamdani reasoning method is suggested. For applying fuzzy reasoning, the measured load bearing – width – clear height values have to be converted to membership functions, by defining the membership values for the corresponding bridge data.

The gained conclusion is a fuzzy set, and because of the simple comparison between bridges it has to be defuzzificated. The "crisp" result of sufficiency is calculated by the center of gravity defuzzification.

1. Condition of the bridge stock

Figure 1. shows the change of the surface and the cost of a centrally managed bridge stock in the course of three decades.

The graph depicts quite well, that the expenditures have significantly changed from year to year, and that the trend has the opposite direction to the steadily growing surface area f bridge stock.

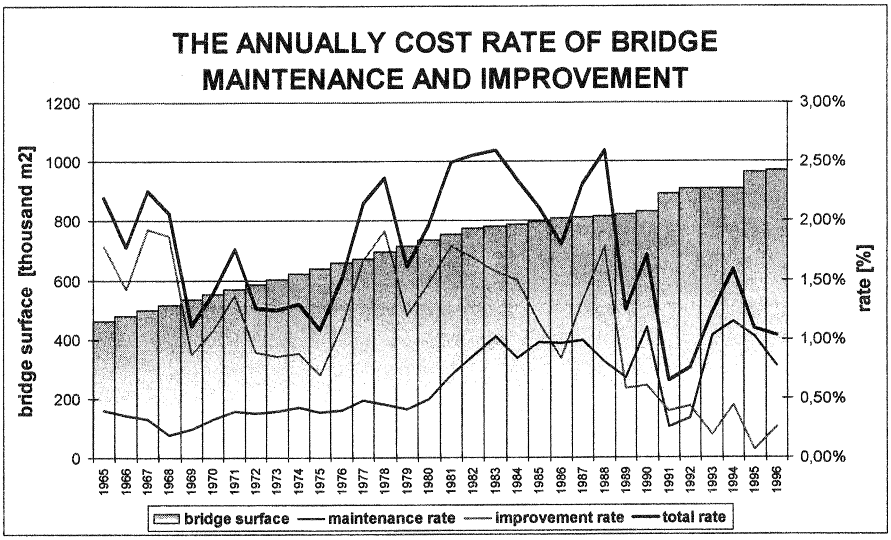

Figure 1.

If we add to this fact the almost exponential traffic growth, the challenge of the Management can be clearly seen: from year-to-year they have to maintain the safety of traffic, sometimes with budgets lower than sufficient, while they have to provide the highest possible quality of services (through traffic capacity, accessibility, travel komfort, and also minimizing the environmental damage caused).

The problems shown in the figure can be further complicated by factor such as:

- the ageing due to the lack of structural replacements,
- the practice of "fire-rescue" type interventions, because of the lack of designable preventive interventions
- moreover the increasing number of vehicles, the growth in the size of maximum individual vehicle weight, and axial load.

The optimal solution for this multi-factorial problem, in respect of the nearly 6000 number national bridge stock cannot be maintained by expert knowledge alone, a sufficient automatic solution, a suitable MANAGEMENT SYSTEM is needed.

2. The management systems

A broader definition of a management system includes the cyclical processes of examination of the stock, data collection, data storage and processing, and execution of the proposed interventions based on data-processing. In a narrower sense, systems dealing with the input data, (quasi)optimizing, and providing results supporting the decision making, are also called management systems. We shall use this narrower definition for bridge management systems.

3. Bridge management systems

The inhomogenity of the stock cause the bridge-management a specific problem: the structural materials-, the method of construction-, the size-, the age- of bridges differ greatly. Due to this factor of the failure-process the suggested repair-works can vary. Expenses of repair can be also studied through economics, statistics, and occasionally economical psychology, but they are beyond the scope of this paper. This paper focuses on the other principle questions of bridge-management: determining the practical (efficient) interventions both on the spatial (which bridge, what structural component) and on the time-scale (when, during which cycle).

4. The "soft" and the "crisp" approaches

Bridge-management systems in use, are proposing the required repair-work in the studied cycle based on the compliance benchmarks and expenditure data algorithmically. Sufficiency is derived by an "IF-THEN" type logical decision, or in more sophisticated applications as a group of parametric decisions. The *sufficiency-factor* in case of one single structure or structural component is always "crisp".

In practice the structure's surveyor is also struggling with the sharp "crisp" boundaries of standards, whether the structural condition or the service quality provided by the structure needs to be rated. The dilemma is especially great in load-bearing-clear-width and height rating: the slightest shortfall against the "crisp" requirements leads the algorithm rating the bridge to be failed, contradicting both the common (technical) sense and the approach to use resources economically.

The contradiction between the "crisp" nature of algorithmically definable standards, and "soft" technical benchmarks derived from professional practice can be resolved with the introduction of "fuzzy logic". Applying *fuzzy logic* the compliance conditions/measures are not crisp values, but defined by fuzzy membership functions.

The proposed solution is not involved in the bridge-managing systems in Hungary yet, but regarded as an alternative innovative direction.

For the first application, the use of the "provided service quality compliance test" would be recommended, as its compliance criteria is well defined, there is no need for too many parameters, and its results can be translated relatively easily based on practical technical knowledge.

Another advantage of fuzzy logic is its anthropomorphic nature: instead of numeric ratings, the surveyor can use (technical)expressions, from his professional experience, sometimes with rather "fuzzy" margins, integrating a number of sufficiency aspects. This "inaccuracy" of the qualification system, makes not only the experienced surveyor team's job easier, but also allows incorporating non-numeric background information, increasing the reliability of the ratings.

5. Sufficiency of bridges with respect to quality of services

The improvement module of the bridge management system rates bridges based on the expected quality of service. At the moment this is done by the comparison of the real and the expected values of three parameters:

- load bearing capacity
- clear width
- clear height

It is evident though, that the proposed set of bridges to be improved (to be improved efficiently regarding the actual technical-economical environment) can only be selected after a complex study of the possible parameters. The present practice applies an algorithmic process, but the utilization of fuzzy theory will provide new and hopefully, a more simple solution, which is also easier to understood and operated by the user.

5.1. load bearing capacity

In order to compare the load bearing capacity of bridges, the operators of the database have to fill a field providing the structures' operational load bearing capacity numerically in tons. The software developer solved the problem of differences in axial distances and loads of real vehicles, by the use of standardized vehicles.
The standard vehicle weights are:

3t, 6t, 9t, 12t, 16t, 22t, 32t, 40t, 80t

Note that at the present vehicles up to 44t gross weight are allowed to use the road without special permit, thus it has to be introduced a 44t weight limit above the 40t service load. In the further discussions we assume its existance.

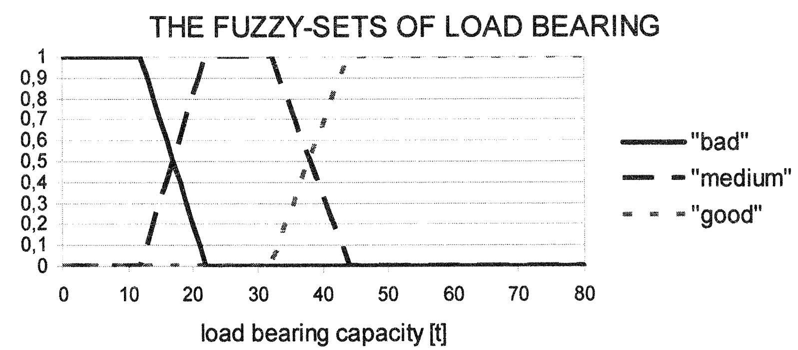

Figure 2.

The 12t capacity is only sufficient for automobiles and lightweight lorries, thus any capacity below this has to be regarded as "bad". The next natural marginal value of load bearing capacity for bridges is 22t, allowing buses (including articulated buses), therefore we cannot call it "bad". The 44t is once again a natural limit: vehicles exceeding this can only use roads with a route permit, thus their route can be planned with respect to bridge load bearing capacity (too). Because of this load bearing capacity over 44t, can be called definitely as "good". Bridges with capacity between 12-44t are rated as "medium", over 22t "good". Figure 2. shows the load bearing sufficiency membership functions (trapezoidal for the sake of simplicity).

5.2. The pavement width

The sufficiency of the pavement width can be determined based on the number of traffic lanes, the road category, the traffic, the bridges length and the bridge's location (rural or urban). In the current (experimental) study we only deal with two-lane roads, disregarding other modifying affects. (Taking these parameters into account is indifferent with respect to the use fuzzy logic, it is only complicating the preparatory work.)

The natural limits for clear width are

$$2\times3{,}25m=6{,}5m,\quad 2\times3{,}75m=7{,}5m,\quad 2\times3{,}75m+2\times0{,}5m=8{,}5m$$

The actual pavement width failing to provide the minimum lane width was clearly rated "not enough", the actual pavement width providing the minimum lane width and the safety add-on was clearly rated "enough". Bridges with conditions in between "not enough" and "enough" are rated "tolerable". Figure 3. shows the pavement width sufficiency membership functions (trapezoidal for the sake of simplicity).

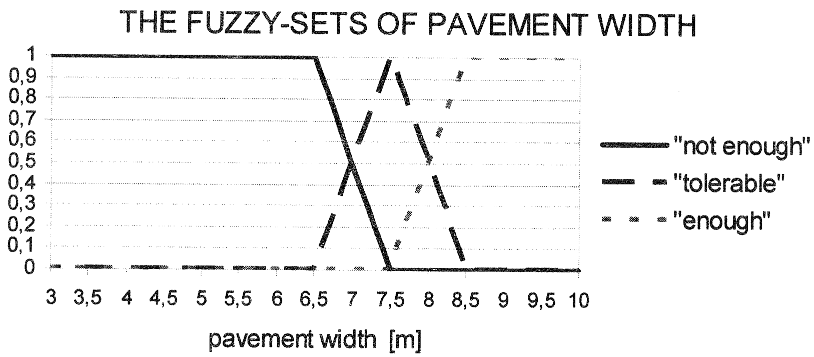

Figure 3.

5.3. The clear height

To comply with the regulations there has to be 4,70m clear height above the pavement, so we have 0,2m safety above the height of vehicles allowed to use on roads without a special permit (4,50m). However among the existing structures there are bridges not surpassing the minimum clear height. The clear height below 4,0m can be evidently called as "short" and above 4,70m as "tall". In this case because of the small difference no intermediate category was introduced, and the intermediate heights are rated overlapping “short” and “tall”. Figure 4. shows the clear height sufficiency membership function (trapezoidal for the sake of simplicity).

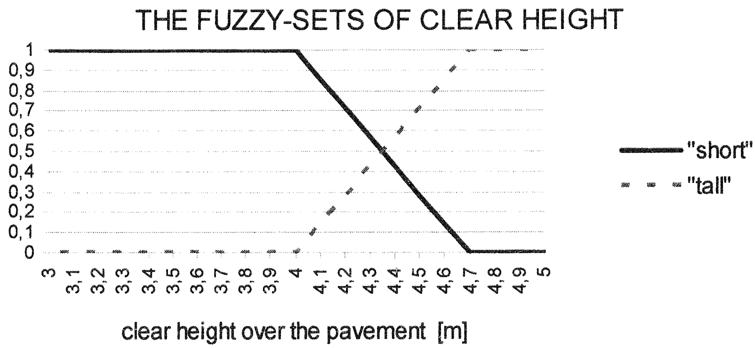

Figure 4.

5.4. Sufficiency in respect to service quality

The complex sufficiency index of bridges incorporating the load bearing-; width-; and clear height sufficiency is described on a 100 grade scale with 10 categories. Figure 5. shows the sufficiency ratings fuzzy membership functions.

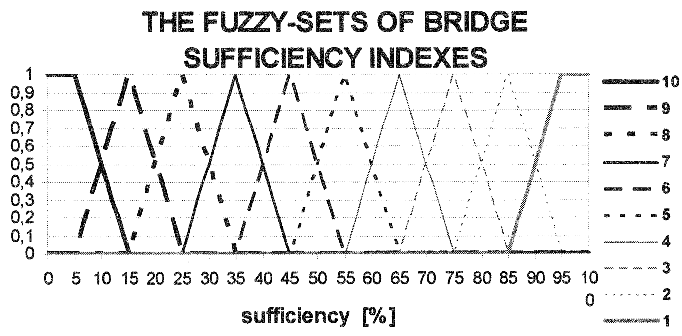

Figure 5.

5.5. The fuzzy rules

The connecting element between the input (load bearing – width – clear height sufficiency data) and the output (complex sufficiency ratings) is the rules of logical preconditions based on the professional knowledge. For every combination of input ratings the rules designate separate complex sufficiency ratings (naturally this rating is a fuzzy set as shown on the figure 5.). It was taken into consideration that the main bottleneck of traffic is the load bearing incapacity, since the width shortage (excluding extreme cases) can be managed by decreasing the flow of traffic, while the shortage of clear height only affects vehicles with tall loads, and great weight.

RULE	1	2	3	4	5	6	7	8	9
INDEX	10	9	7	8	7	5	5	4	2
load bearing	bad	bad	bad	medium	medium	medium	good	good	good
pavement width	not enough	tolerable	enough	not enough	tolerable	enough	not enough	tolerable	enough
clear height	short	short	short	short	short	short	short	short	short

RULE	10	11	12	13	14	15	16	17	18
INDEX	9	8	6	7	6	4	4	3	1
load bearing	bad	bad	bad	medium	medium	medium	good	good	good

In the 3D matrix of figure 6. the rules connecting the output rating with the input category combinations are clearly shown graphically.

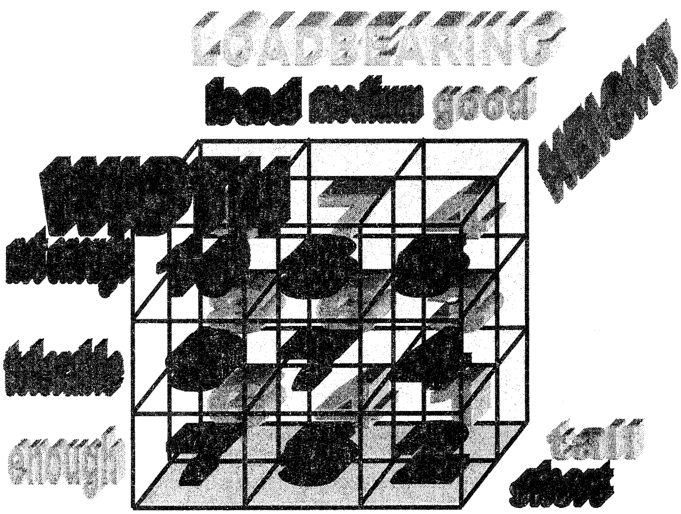

Figure 6.

6. The fuzzy conclusions

For executing the fuzzy deductions, in this paper the Mamdani reasoning method is suggested. For applying fuzzy reasoning, the measured load bearing – width – clear height values have to be converted to membership functions, by defining the membership values for the corresponding bridge data. These membership values show us, to what degree does the specific bridge meet the qualification described by the corresponding membership function. The fuzzy rules designate an output sufficiency rating for every membership function combination, and according to Mamdani reasoning, in the final fuzzy conclusion this rule plays a part proportionate to the minimum values of the respective membership values. If multiple rules give the same output rating, then the union of the conclusions given by the individual rules were applied, which can be deducted as the minimum value of the similarly rated membership values.

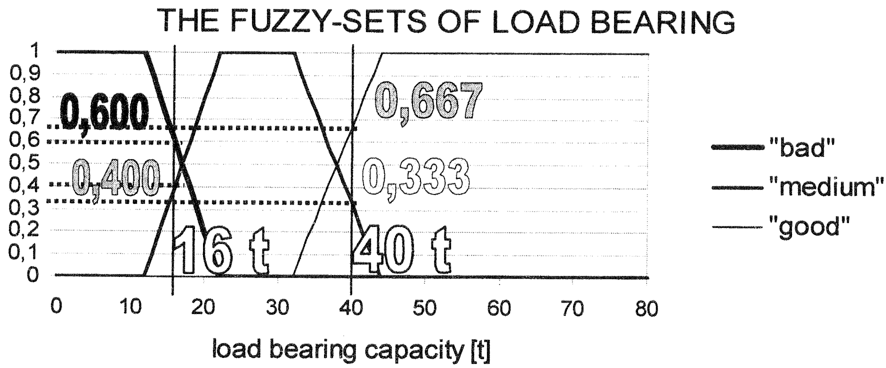

Figure 7.

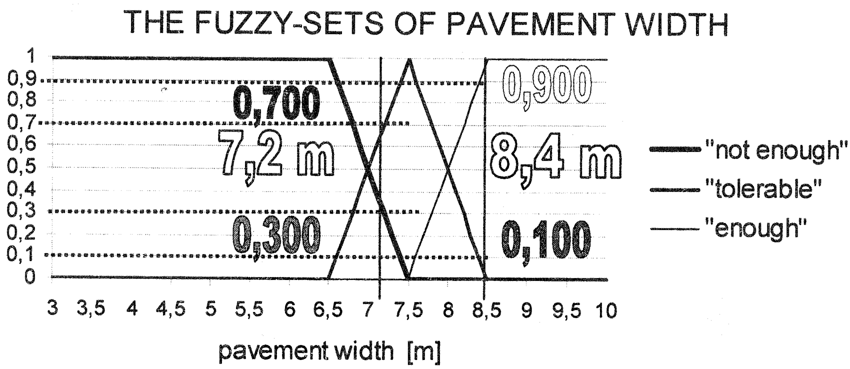

Figure 8.

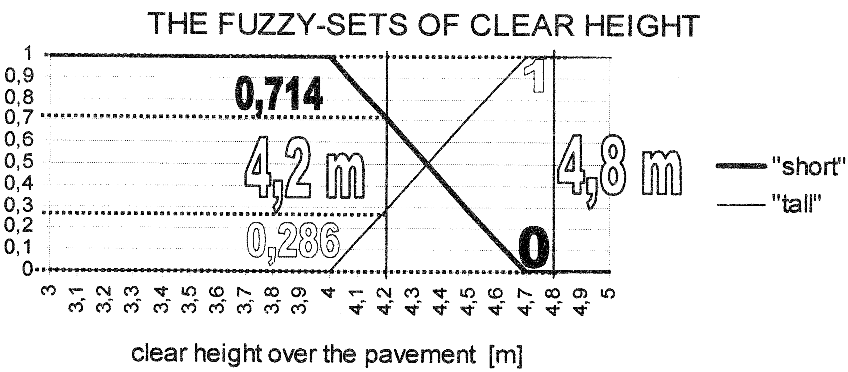

Figure 9.

THE MINIMUM OF THE MEMBERSHIP VALUES

	DATA OF BRIDGE			BRIDGE SUFFICIENCY INDEX									
	LB	W	H	10	9	8	7	6	5	4	3	2	1
A	16	8,2	4,8	0,000	0,000	0,300	0,000	0,600	0,000	0,400	0,000	0,000	0,000
B	40	7,4	4,2	0,000	0,000	0,100	0,333	0,286	0,100	0,667	0,286	0,000	0,000

7. The sufficiency value of the bridge

The gained conclusion is a fuzzy set, and because of the simple comparison between bridges it has to be defuzzificated.

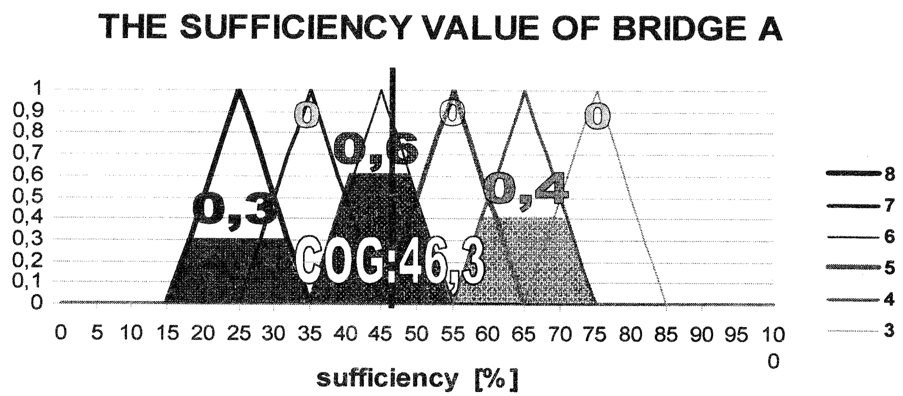

Figure 10.

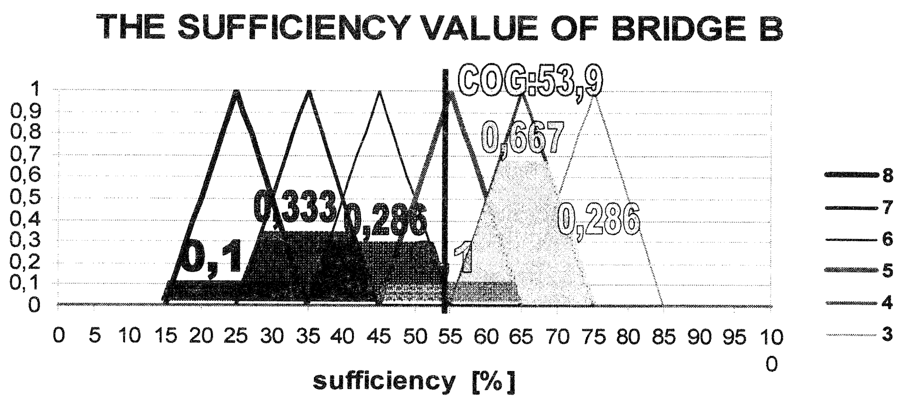

Figure 11.

The "crisp" result of sufficiency is calculated by the center of gravity defuzzification. Due to the linearity of the fuzzy sufficiency membership functions the crisp conclusion can be easily calculated. In other words we can get the examined bridge's complex sufficiency rating by fuzzy technique.

8. Other possibilities of use

Besides providing the ranking of bridges for improvement, fuzzy logic can be beneficial in determining the bridge's integrated status as well. Bridges consist of many structural elements and components. These components are influencing the risk of failure to a very different degree. In the course of the annual bridge examination the state of every element and component is recorded, but only the state of the five major structural elements' and components' are entered into the official database. Based on the bridge expert's knowledge, an integrated status characteristic of the major structural components, or even of the whole structure could be taken into consideration with the use of fuzzy technique for bridge evaluation. However the method introduced in this paper is just a possible solution yet, more improvements can be expected in the following years.

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