Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)
31 May – 1 June 2018, Singapore
Editor(s) Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon

MAINTAINING AN AGING INFRASTRUCTURE BASED ON A FUZZY RISK ASSESSMENT METHODOLOGY

ANDREAS PANENKA[1] and FRANÇOIS MARIE NYOBEU FANGUE[1]

[1]*Departement Structural Engineering, Federal Waterways Engineering and Research Institute, Karlsruhe, Germany.*
E-mail: andreas.panenka@baw.de
E-mail: francois.nyobeu@baw.de

This paper presents how a Failure Mode and Effect Analysis (FMEA) with fuzzy logic-based aggregation of the assessments criteria provides decision maker with key figures concerning the risks emerging from aging civil engineering structures. The determination, adaptation and calibration of both the FMEA and the assessment criteria draw on a variety of already available information sources. Inspection data repositories and the maintenance management system help to set-up the relevant cause-and-effect chains and the respective failure modes. The risk factors are adapted to the specific influences regarding civil engineering structures and calibrated based on available data and expert knowledge. The aggregation of the risk factors applies Fuzzy Logic to obtain relevant key figures, like risk priority numbers or risk profiles. Using the example of the prioritization of maintenance measures for weir gates on a river in Germany illustrates the benefits of the developed key figures.

Keywords: FMEA, Maintenance Management, Risk Profile, Fuzzy Criticality Assessment

1 Introduction

Civil engineering structures are designed to fulfil an intended function within a specific lifetime. Although these structures deteriorate over time, their reliability must meet the requirements defined in the up-to-date standards at any time. Thus, the structures require permanent maintenance in order to keep their structural condition and reliability. The larger the portfolio of structures the more important is a maintenance management system (MMS) with expressive key figures allowing a prioritization of maintenance work in order to use the available resources most effectively.

The German Federal Waterways and Shipping Administration (WSV) is responsible for several thousand structures. The Federal Waterways Engineering and Research Institute (BAW) as technical advisor to the WSV developed a procedure based on a Fuzzy-FMEA to produce the required expressive and differentiated key figures using the available condition assessment data.

2 Condition Assessment Methodologies

A strong indicator of the ability to fulfil functional requirements is the actual condition of the structure. Thus, the MMS of the responsible transport administrations in Germany all rely on periodic visual inspections to assess the actual condition of the structures. Every irregularity and damage is documented, classified and filed in a damage data repository. These damage data is then used to evaluate the actual condition of each structure. If the resulting key figures of the evaluation process represent not all influencing factors, they will lack expressiveness to be used for the prioritization of maintenance work. For example, the WSV uses a condition rating system without reference to functional and structural requirements of the assessed structures. Owing to an increasing maintenance backlog such simplifying rating systems are deemed insufficient because too many structures have already been rated with the worst possible condition. Thus, the necessity of developing additional, more expressive key figures becomes a foremost imperative.

3 FMEA in Maintenance Management

3.1 *FMEA and civil engineering structures*

Generally, FMEA is a systematic and analytic method of risk assessment. It is used to identify the most critical components of a system and, thus, developing improvement strategies, which aim at achieving its required reliability or safety. As such, the analysis considers all relevant information about the assessed item (i.a. Stamatis, 1995). Regarding civil engineering structures, this information specifically encompass aspects related to events acting on a system; corresponding system responses and the value of the system at risk (see Table 1). Information about these aspects is derived, amongst others, from damage data repositories, structural assessments, system definitions and expert knowledge.

Table 1. Relevant factors in the risk assessment of civil engineering structures

Influence	event	system	value
Criteria	occurrence (O)	maintainability (D)	severity (S)
Indicator	damage case	extent of deterioration	ease of structural verification
Measure	frequency (f)	specific condition grade (CG_{spec})	structural robustness (-)

3.2 *Damages and cause-and-effect chains*

A fundamental part of the FMEA consists of establishing a causal relationship between the functional requirements of a component and potential failure modes (FM) by means of cause-and-effect chains. Documented damages cases may be considered as indicators of such FM. Thus, using damage data repositories to establish the cause-and-effect chains link typical damage cases to specific FM and subsequently to the requirements they affect. This link allows the calculation of specific condition grades (CG_{spec}) as function of affected requirements; information, which may not be represented by a general condition grade (CG_{gen}) in its entirety.

3.3 *Criticality assessment in context with maintenance management*

The criticality assessment by means of a FMEA ranks the cause-and-effect chains according to their risk priority. The determination of the risk priority is based on the occurrence of a failure (O), the severity of its consequence (S) and the effectiveness of counter measures preventing the consequences (D). Each of the three risk factors has a typical indicator and a corresponding measure. Table 1 gives an overview of this relationship when applying a FMEA to civil engineering structures.

The calibration of the scale for the occurrence uses statistical evaluation of available damage data repositories. The more structures show a certain FM the higher the rating. The scale for the maintainability is based on the extent of deterioration, implying that the poorer the actual condition is the harder it is to maintain the structure. The severity of a failure consequence is efficiently assessed based on expert knowledge or detailed structural analyses.

Using the three risk factors, the risk priority number (RPN) of each cause-and-effect chain is calculated. Risk profiles summarize the RPN of each FM in one diagram (see Figure 3).

Beside the general and specific condition grade, RPN and risk profiles are additional key figures supporting the decision-making process regarding the prioritisation of maintenance measures.

4 Fuzzy Criticality Assessment

4.1 *Procedure*

The traditional way of calculating the RPN as product of the three risk factors has several shortcomings, summarized by Liu (2016). Hence, the preferred aggregation method in many practical applications uses Fuzzy Logic to mitigate some of the main drawbacks of the traditional approach (Bowles and Peláez, 1995). The proposed procedure based on Fuzzy Logic consists of four components, namely fuzzification of the input parameters, fuzzy rule base, fuzzy inference process and defuzzification. In terms of Fuzzy Criticality Assessment (FCA), fuzzification means to translate the assumedly precise, i.e. crisp, input variables into linguistic expressions. When it comes to judge potential risks of a system or structure, the usage of such linguistic expressions may feel more natural than numeric values. Each crisp input value has then a certain degree of membership μ(x) to one or more linguistic expressions (see Figure 1).

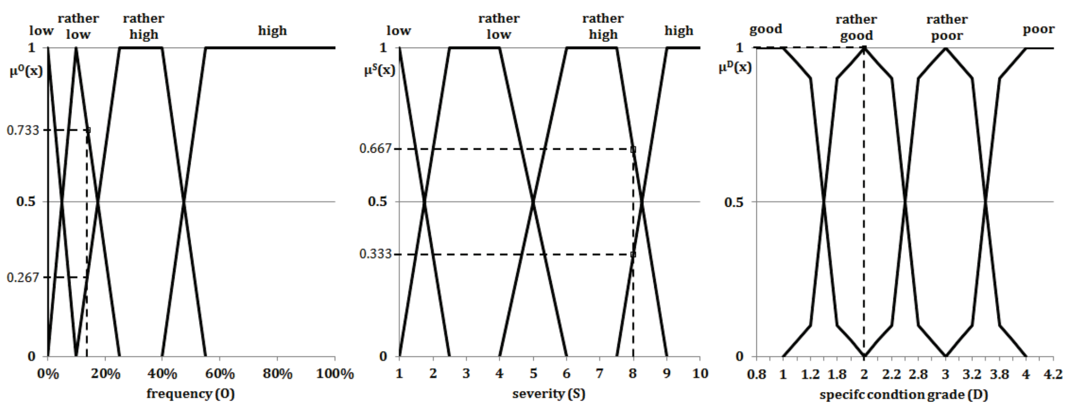

Figure 1. Fuzzy sets of the risk factors with exemplary readings

The further assessment is done by operating with these linguistic expressions of the input variables and the corresponding degree of membership (cf. Figure 2). Sets of "If-Then" rules connect each combination of fuzzified input variable (antecedent) with the corresponding output (consequent). For example: "IF the occurrence is rather low AND the severity is rather high AND the specific condition grade indicates a rather good maintainability THEN the risk priority is moderate." The degree of fulfilment (DoF) of each consequent is determined based on the degrees of membership of the corresponding rule antecedents. There exist several procedures for this evaluation to a fuzzy conclusion. Rommelfanger (1994) considers the max-prod-inference (Larsen method) more in compliance with analyses similar to FMEA, which perform a fuzzy evaluation only once to obtain a result. By means of the max-prod-inference, the fuzzy set of the rule consequent is scaled based on the resulting DoF. Hence, the max-prod-inference conserves the original shape of the conclusion set, which has a value of its own regarding a graphical evaluation of the conclusion. If any fuzzy output is a consequent of more than one rule, the same author suggests using the algebraic sum to calculate the resulting DoF. There are several methods to obtain crisp values of RPN as result of the fuzzy conclusion. In this case, the defuzzification uses the weighted mean of maximum (WMoM; Bowles and Peláez, 1995).

4.2 *Output of the fuzzy criticality assessment*

The Fuzzy Logic-based approaches "gives a more flexible structure for combining the severity, occurrence and detectability parameters" (Bowles and Peláez, 1995) than a linear multiplication of three crisp input values. A rule base determined by means of expert knowledge may implicitly contain a weighting of the different parts of the antecedent, which is a desirable side effect regarding the expressiveness of a FMEA. Furthermore, the fuzzified procedure provides different representations of the results of the criticality assessment. Depending on the context, the resulting risk priority could be expressed numerically (RPN = 250), linguistically ("high" risk priority) and graphically (risk profiles and output fuzzy sets). Figure 2 exemplary shows the procedure for one set of input values. A linguistic expression for the determined risk level could be: "The risk level of this FM is moderate to rather high with some tendency to high."

			antecedent		rule base	consequent			RPN
risk factor	measure	input	fuzzy in	μ		fuzzy out	DoF	alg. sum	WMoM
S	(-)	8	RH	0.667		M	0.667	0.667	627
			H	0.333		RH	0.333	0.689	
O	f	14%	RL	0.733		RH	0.267		
			RH	0.267		H	0.267	0.267	
D	CG_{spec}	2	RG	1.000					

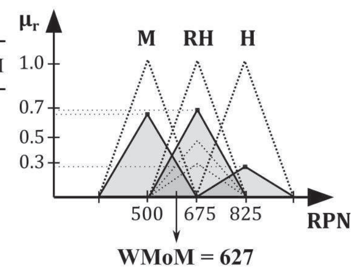

Figure 2. FCA with max-prod-inference; aggregation through algebraic sum and WMoM; exemplary

5 Case Study

Using the example of four weirs with in total 12 weir gates illustrates how a fuzzy FMEA for civil engineering structures effectively creates a ranking based on the condition of the structures. The four weirs are operated on the federal waterway *Neckar,* which is located in the south-west of Germany. The WSV is the responsible authority for this river.

5.1 *Available key figures in the MMS of the WSV*

The MMS of the WSV uses a condition assessment procedure resulting in single key figures. These general condition grades (CG_{gen}) does not allow specific conclusions about the effects of the identified damages on functional or structural requirements. Yet, ten of the 12 weir gates are rated with highest possible general condition grade of 4. A prioritization of maintenance activities based on this single key figure is thus not possible.

5.2 *FMEA of weir gates*

Weir gates are hydraulic steel structures (HSS) regulating the water level of the impoundment. Beyond various structural characteristics of these weir gates, the load-bearing capacity of the gate body is the only structural requirement investigated in this case study. The assessment is based on available data and algorithms already implemented in the MMS of the WSV.

The qualitative analysis of the damage data repositories identifies the major cause-and-effect chains, which may affect the verification of the structural safety of the gate body. Due to this link serving as data filter, the algorithm for calculating the condition grade considers only damages relevant for the respective FM. The assessment of weir N., bay 2 demonstrates the effect of this filter. CG_{gen} of the gate is 4, considering all damages. Considering only damages, which directly affect the load bearing capacity, results in a lower, i.e. better, specific condition grade ($CG_{spec,LBC}$) of 2 (see Table 2).

5.3 *Fuzzy criticality analyses of the gates*

Figure 1 presents the fuzzy sets of the input variables. The statistical analyses of the data reveal the damage frequency. The FM, which occurs most frequently, is corrosion, affecting 73 % of the inspected HSS. A frequency around and above this value is considered high. There are several other FM (e.g. loss of fasteners) concerning around 20 % to 30 % of the HSS, which is assumed a rather low to rather high frequency range. Most of the identified FM have a low frequency of around 5%. The fuzzy sets of the risk factor "occurrence" are defined accordingly. The specific condition grade for each FM is the measure for the risk factor "maintainability". The fuzzy sets are based on the linguistic interpretation and the value ranges of the general condition grades, which are both already provided by internal inspection guidelines of the WSV. The severity of each FM was defined through a pair-wise comparison of the impact of each FM on relevant verifications including fatigue, buckling, load bearing and deformation. The fuzzy sets of the risk factor "severity" were defined through expert knowledge. The rule base for the aggregation of the risk factors is as well based on expert knowledge. A general differentiation between gate types is possible but was not regarded necessary at this stage of the analysis. The output fuzzy sets comprises of seven membership classes ranging from "negligible" to "critical".

5.4 *Ranking based on extend set of key figures*

Figure 3 shows the risk profiles of the analysed weirs. The risk profile represents the maximum RPN of each FM over all gates of each weir. The profile shows that weir D. displays FM 4 and 5 with a RPN of 1000 and FM 9 above 800. In comparison to the other weir gates, this is assumed to be the most critical weir. It is ranked with the highest priority for refurbishment. Weir W. is ranked above weir B. because it is affected by more FM. Although weir N, bay 2 is also rated with a CG_{gen} of 4, the risk profile shows a risk level much lower compared to the other three weirs. It is thus ranked with the lowest priority. The assessment resulted in the ranking shown in Table 2.

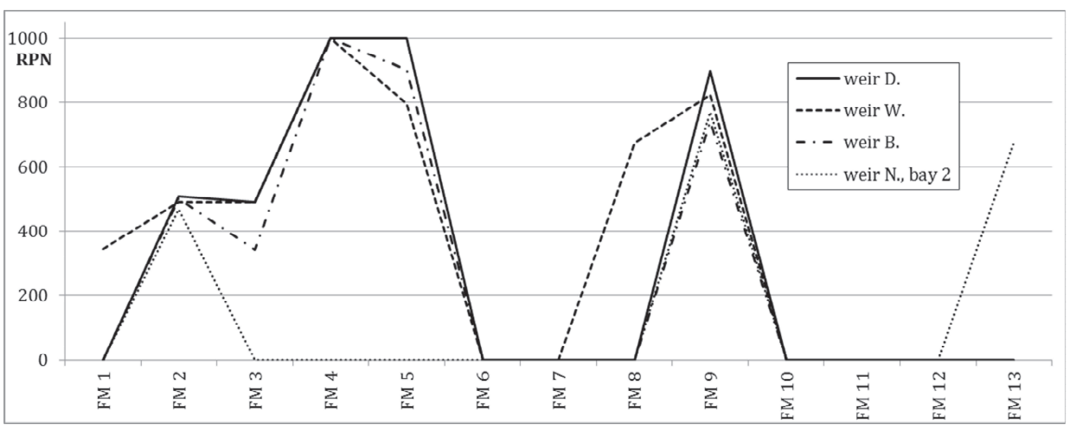

Figure 3. Risk profile of the weirs assessed with the fuzzy FMEA procedure for MMS

6 Conclusion

The described concept of a fuzzified FMEA for civil engineering structures provides important knowledge as well as several comprehensive and meaningful key figures, which strengthen the significance of the condition assessment of aging civil engineering structures. The analysis of qualitative data to establish the cause-and-effect chains provides a holistic view of the relationship between types of damages and their effects on relevant requirements. Several key figures based on qualitative and quantitative data are used to precisely describe the condition of the structure under consideration of relevant requirements. The case study illustrated how the implementation of a Fuzzy Logic-based FMEA enhances the existing MMS of the WSV. Although the assessed structures have the same general condition grade, the presented assessment procedure identified a ranking of the structures regarding for the prioritization of maintenance measures based on the specific condition grades and the risk profiles.

The first trial applications show promising results. Current developments concern the definition of an indicator and its measure for the risk factor "severity" based on advanced structural analyses. Further, the generated key figures shall be implemented in a risk classification methodology for waterway infrastructures (see Schmidt-Bäumler, 2017). Hence, an efficient automation of the assessment procedure as well as the validation of the Fuzzy Logic-approach by means of sensitivity analyses and expert interviews is scheduled for the upcoming research phase.

Table 2. Summary of the numeric assessment results and ranking of the weirs

Weir	type	Bay No.	CG_{gen}	$CG_{spec,LBC}$	RPN_{max}	**Rank**
D	vertical lift	1	4	4	1000	**1**
		2	4	4	1000	
		3	4	4	1000	
W	vertical lift	2	2	2	675	**2**
		5	3	3	825	
	roller drum	1	4	4	825	
		3	4	4	1000	
		4	3.9	3.9	821	
		6	3	3	675	
B	vertical lift	1	4	4	1000	**3**
		2	3.2	3.2	842	
		3	4	4	1000	
		4	4	4	1000	
N	vertical lift	2	4	2	770	**4**

Acknowledgments

The "BMVI Network of Experts", a multidisciplinary research program by the German Federal Ministry of Transport and Digital Infrastructure, financed and supported this work.

References

Bowles, J. B. and Peláez, E. C., Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis, *Reliability Engineering & System Safety,* 50 (2), 203–213, 1995.

Liu, H.-C., *FMEA using uncertainty theories and MCDM methods*, Springer, Singapore, 2016

Rommelfanger, H. J., *Fuzzy Decision Support-Systeme – Entscheiden bei Unschärfe*, Springer, Berlin, Heidelberg, 1994

Schmidt-Bäumler, H., Risk-based maintenance management system for waterway infrastructures in Germany, in *Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure*, Bakker, J. et al. (ed.), 559-566, Taylor & Francis Group, London, 2017

Stamatis, D. H., *Failure mode and effect analysis. FMEA from theory to execution*, ASQC Quality Press, Milwaukee, Wis, 1995.