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Fuzzy Risk Evaluation in Failure Mode and Effects Analysis: A Risk-Based Approach for ranking Infrastructure Assets for Maintenance Interventions

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Number of existing infrastructure assets of the waterway infrastructure portfolio, built prior to the1900s is still in use today. While these infrastructures have already exceeded their expected service lifetime of 100 years, they are exhibiting complex deterioration mechanisms that do not only impair their structural reliability as well as availability, but also pose substantial threats to the social and economic growth of Germany. In response to ongoing degradation processes, associated to combined effects of aggressive environmental stressors, operating conditions and deferred maintenance, a Maintenance Management System (EMS-WSV) has been set up from 2008 by the Federal Waterways Engineering and Research Institute (BAW). Condition grades developed within the EMS-WSV serve for decision making regarding maintenance interventions. However, these condition grades do not sufficiently address the effects of deterioration mechanisms on the structural reliability of waterway infrastructure assets and the emerging risk of infrastructure failure is not also taken into account. The aim of the present paper is to use a very simple approach, namely the Fuzzy Failure Mode and Effects Analysis (Fuzzy-FMEA), to derive additional key figures, taking into account the aforementioned shortcomings. The proposed approach is implemented in this research to rank seven navigation locks of the Main-Danube-Canal (MDK) for maintenance interventions. Due to the complexity of their structural design, reinforced concrete infrastructures pose the most serious risks of infrastructure failure. Thus, fatigue induced-damage, corrosion of the steel reinforcements and inaccuracies in load assumptions are identified as main causes of failure that may hinder the load carrying capacity of these structures.

Keywords: Failure Mode and Effects Analysis (FMEA), Risk Priority Number, Repair and Maintenance interventions, structural reliability, deterioration mechanisms, fuzzy logic.

1 Introduction

The sustainable growth of the German economy largely depends on the structural condition and capacity of its transportation system. Thus, various modes of transport infrastructures, including roads, railways and waterways that facilitate the movement of people and freight traffic are of outstanding importance for the German economy. For example, major waterways serve for freight transport, while connecting the country to Europe and the world. These waterways constitute one of the main pillars of the German important logistics chains for national and international trade of industrial products and crude oil. Alongside these main waterways, minor environmentally friendly waterways, primarily serve for leisure activities (tourism and sport) and water withdrawal for diverse purposes. Moreover, nature conservation and sustainable tourism are currently at the forefront of concerns within the framework of the water tourism strategy in Germany. Thus, maintenance and upgrading measures are necessary to increase the attractiveness of these minor water bodies.

However, both major and minor waterway infrastructure assets have been for years exposed to changing environmental and operational conditions. As a result, coupled effects of, environmental stressors, operational conditions and ageing have contributed to the degradation of the structural reliability and performance of these facilities. While facing challenging environmental conditions, the structures have not always been properly mended. The resulting burden of deferred maintenance interventions is increasingly becoming an issue of a great concern. However, given the diversity of the infrastructure portfolio of the WSV, the selection of structures for maintenance purposes, must be supported by expressive and conclusive key figures. While describing the structural reliability of the assets, the generated key figures must also address the emerging risk of infrastructure failure. At the same time, the structural effects of various deterioration mechanisms on the normative requirements of these facilities must be assessed.

This paper presents a simple technique of risk assessment, used to infer additional key figures, which serve the selection of infrastructure assets for maintenance interventions. Thus, Cause- and Effects Chains (CEC) are developed to assess the structural consequences of different deterioration mechanisms on the normative requirements of the infrastructure. Numerous risk assessment techniques in various sectors, including aerospace, nuclear, automotive, chemical and mechanical industries are available in the literature as contended by Liu (2016). Yet, the qualitative nature of the raw data (damage data, collected during cyclic visual inspections) led to the implementation of a semi-quantitative assessment approach. Taking into account expert knowledge and uncertainties, inherent to the available damage data, the Failure Mode and Effects Analysis (FMEA) is implemented to identify the most critical failure modes.

The outcome of the FMEA-analysis is likely to be altered by uncertainties, involved in data collection and evaluation. At the same time, various limitations of the traditional FMEA-methodology must be accounted for in achieving a rational decision making (Bowles and Peláez 1995; Braglia et al. 2003a; Bai et al. 2006; Liu 2016). Aiming at improving the decision making ability of the FMEA, both uncertainties and limitations of the FMEA are covered based on Fuzzy Logic (FL) analysis, following the study of Bowles and Peláez (1995). The rest of the paper is structured as follows: section 2 provides more insights about background information that have triggered this study. Details of the application of both the FMEA and the Fuzzy Logic to waterway infrastructure assets are described in section 3. Then, section 4 introduces a case study, while main findings are discussed in section 5. Finally, section 6 discusses the contribution of this paper in shedding more light on the challenging issue of decision making regarding repair and maintenance interventions. Limitations of the current approach and further research directions are also proposed.

2 Background

The vast majority of infrastructure assets, built in the late 19th and the beginning of the 20th century is now of considerable age. Indeed, the German portfolio of inland waterway infrastructure assets, including navigation locks, weirs, floodgates, canal bridges, culvert systems, bridges, etc. is aging. For example, roughly 41% and 47% respectively of navigation locks and weirs of the inspection category A are currently 80 years old. More specifically, 13% and 18% respectively of navigation locks and weirs, some of which are still in use, have already exceeded their intended design-service lifetime of about 100 years.

Although many of these facilities were constructed prior to the 1950s, the bulk of these infrastructure assets have neither always been properly mended nor updated. In addition to aging, waterways infrastructure assets, with particular reference to navigation locks and weirs of the inspection category A, are in some cases in a critical structural condition. Within the updating of the administrative regulation VV-WSV 2101 for waterway infrastructure assets inspection, the facilities are divided into three main inspections categories (A, B and C), taking into account risk potential and complexity. It is generally admitted that all waterway infrastructure belong at least to the inspection category C. At the forefront of this hierarchy, infrastructure assets exhibiting both a high risk potential and typical complex characteristics are classified as inspection category A (BMVI 2018).

Essentially, the bulk of navigation locks and weirs of the WSV belong to the inspection category A and plays a crucial role in inland navigation in Germany. Because of their importance for the navigation and their ongoing deteriorating condition, these facilities are granted a particular attention with regard to maintenance and renewal interventions within the WSV. It should also be noted that damage data, collected during cyclic visual inspections, are rated using a scale from 1.0 to 4.0 (1.0 describing a good condition and 4.0 depicting a critical condition). While depicting the effects of identified damages on the structural reliability of the structure, these values are clustered into four classes for assessment purposes, as shown in Figure 1.

Importantly, damages rated with a damage class between 3.5 and 4.0 are likely to impair not only the load carrying capacity as well as serviceability, but also the durability of the structure. Beyond indicating the neediness of maintenance interventions, various infrastructure assets with an overall condition grade up to 4.0, constitute the current burden of maintenance interventions. As an illustration, 40% and 26% respectively of navigation locks and weirs are in a critical condition (condition grades between 3.5 and 4.0). Equally noteworthy, 12.6% of weirs and 24% of navigation locks, with specific reference to solid construction “Konstruktion” are in a critical condition. Similarly, the number of assets, with solid construction in a poor condition, is significantly high for navigation locks and weirs, respectively 57.9% and 55.2% (see Figure 1).

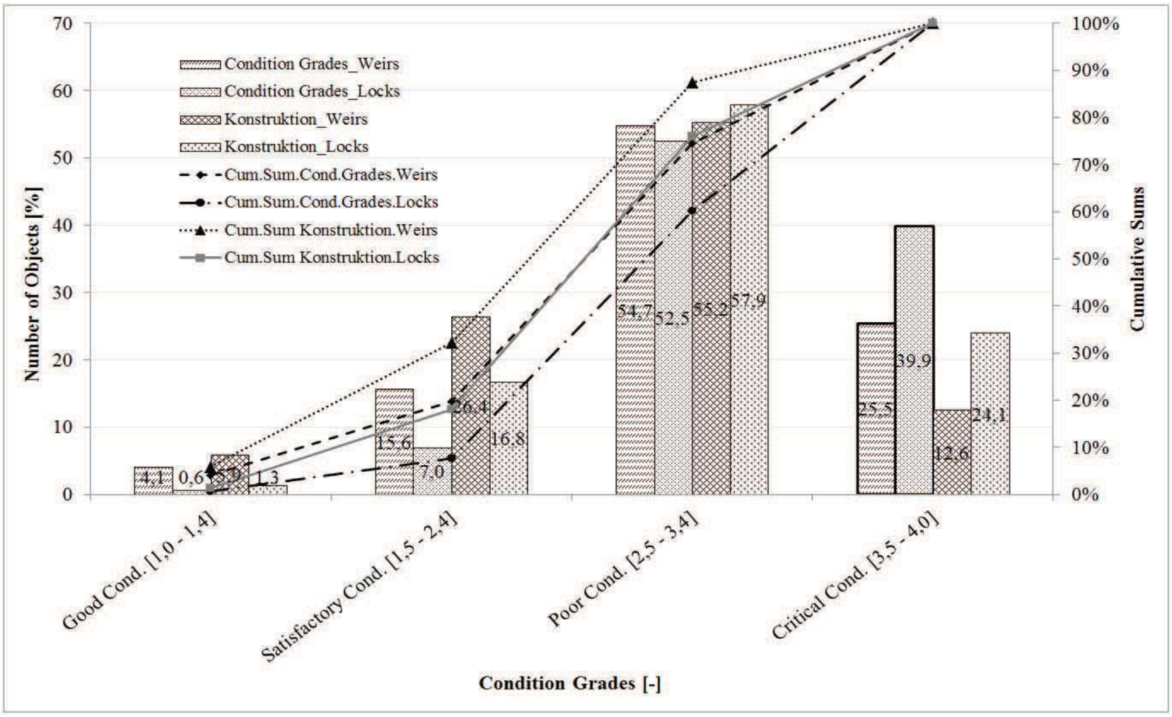

Figure 1: condition grades of the solid construction "Konstruktion" and overall condition grades of navigation locks and weirs of the network category A

In compliance with the abovementioned administrative regulation VV-WSV 2101, observed damages are collected, evaluated and documented during cyclic visual inspections in the software program WSVPruf (BMVI 2018). These data are used to generate condition grades that depict the effects of various damages on the structural reliability of the structure. Although the obtained condition grades are used to enhance decision making regarding maintenance interventions, they do not explicitly address the emerging risk of infrastructure failure. Also, due to deferred maintenance interventions, the number of infrastructure assets that must be maintained have extensively grown. Consequently, there is an imperative need of developing additional key figures, taking into account the aforementioned limitations, which can be used for prioritisation of maintenance interventions. Thus, the fuzzy-FMEA method, used for the generation of further key figures in this study is explained in the next section.

3 Methodology

Damage data, collected during regular visual inspections are mainly of qualitative nature. Thus, based on qualitative methods, expressive key figures could be inferred in the present study. At the core of the FMEA methodology, various causes-and-effects-chains (CEC) are identified and their effects on the structural reliability of waterway infrastructure assets are assessed. Various CEC are assessed using three main risk factors, including the severity (S), occurrence (O) and detection (D). However, the evaluation procedure of the risk factors is based on expert knowledge and experience of the multidisciplinary FMEA-Team. It is thus obvious that the results of the FMEA are likely to suffer some uncertainties and to confront several criticisms. To overcome some these shortcomings, the Fuzzy logic is used in this study to convert the vagueness of human expertise as well as experience and its decision-making ability into a mathematical formula (Braglia et al. 2003a; Liu 2016). It should also be noted that this methodology provides meaningful representation of measurement for uncertainties and vague concepts expressed in natural language (Bowles and Peláez 1995).

3.1 Failure Mode and Effects Analysis (FMEA)

First applications of the FMEA are traced back to 1949. The method was used by the US Army in the aeronautic to solve reliability and safety problems during the design and production phases (Paciarotti et al. 2014). Since then, the method has been successfully employed for quality and reliability assessment in various sectors, including aerospace, nuclear, automotive, electronics and mechanical industries. However, specific applications of the FMEA for the improvement of the structural reliability of civil engineering infrastructures are not always reported in the literature.

Liu (2016) defines the FMEA as "*a systematic methodology designed to identify known and potential failure modes and their causes and the effects of failure on the system or end users, to assess the risk associated with the identified failure modes and prioritize them for proactive interventions, and to carry out corrective actions for the most serious issues to enhance the reliability and safety of products and processes, designs or services*". Basically, the conventional FMEA consists of two main steps, namely the analysis of the system and the risk assessment. Yet, these steps can be broken down into five phases, including:

- analysis of the structure,
- analysis of various structural functions,
- Analysis of various failure modes,
- Criticality assessment or risk evaluation,
- Identification of remediation measures.

Because the identification of remediation measures is far beyond the scope of this study, this particular aspect will not be discussed further in this paper.

3.1.1 Scope definition/Structure analysis

The aim of this step is to establish a hierarchical system of various components of the structure in order to identify the components with high risk potential for further analysis. For example, a navigation lock consists of 11 object subcategories, including "solid construction", "steel construction", "joint tapes", "sealing elements", "drives", "Bearings & rollers", "fitting/ equipment", "corrosion protection", "mooring devices", "floor and bank constructions", and "others". Using both pairwise comparison analysis and Quality-Function-Deployment (QFD)-Matrix, the subcategories "solid construction", "steel construction", "joint tapes", "Bearings & rollers", "drives", "sealing elements" are identified as essential components for which a FMEA could be performed.

3.1.2 Function analysis

The functional analysis has two main objectives:

- to identify the main and secondary functions of various subcategories, analyse the load paths and determine the main features of each function with respect to different subcategories,
- to display functional relationships among different object subcategories (functional network).

3.1.3 Failure analysis

Having determined various main and secondary functions of each subcategory, potential failure modes that are likely to impair these functions are identified. In a conventional FMEA, a failure is described as a non-fulfilment of an intended function (Bertsche et al. 2009; Liu 2016). Accordingly, a failure of a subcategory of a navigation lock consists in its inability to meet the normative requirements, including load-carrying capacity, serviceability and durability. Thus, based on expert knowledge different cause-and-effects-chains (CEC), describing the relationship between potential failure modes (FM), failure consequences (FF) and causes of failure (FC), are developed (Fig 2). With particular reference to navigation locks, 13 causes of failure, associated with various structural deterioration mechanisms of reinforced concrete, are identified within the framework of this study.

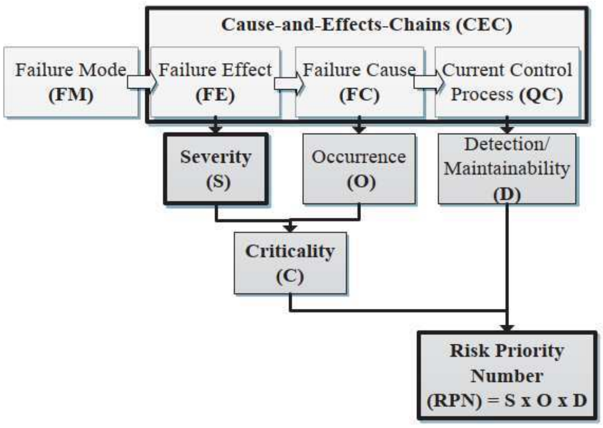

Figure 2: Qualitative risk assessment procedure

3.1.4 Criticality analysis or risk assessment

Risk assessment is at the core of the FMEA. In a conventional FMEA, the criticality or risk assessment of various CEC determined by the Risk Priority Number (RPN) (Gilchrist 1993; Bowles und Peláez 1995; Braglia et al. 2003a); Liu 2016). In a conventional FMEA, the RPN is evaluated as the product of three risk factors, including the probability of occurrence (O) of a failure, the severity (S) of its consequences and the probability of the cause of failure being detected (D). Hence, using available data and based on expert knowledge of processes or products conventional rating tables have been developed in various sectors. While these conventional tables serve for the evaluation of the different risk factors, they are based on a scale ranging from 1 to 10, low to high. However, it is important to stress that in practical situations, the obtained RPN are primarily useful for the identification of critical failure modes and the way in which they may affect the intended functions of the structure. Therefore, the RPN values provide not only key information about the level of riskiness of various CEC, but it is also used to enhance decision making about prioritization of corrective interventions (Ekmekçioğlu and Kutlu 2012; Liu et al. 2013b).

3.2 Fuzzy Logic (FL)

3.2.1 Limitations of the FMEA method

The conventional FMEA often suffers a number of limitations that are either associated with uncertainties in the evaluation procedure of the risk factors or the criticality assessment procedure. Thus, some of the overriding limitations of the conventional FMEA include:

- Diverse combinations of S, O and D may lead to the same RPN value, although their hidden risk implications may be absolutely different. For example, two different failure modes with S, O and D values of 5, 8, 2 and 2, 10, 4 respectively, have the same RPN value of 80. However, the hidden risk implication of the second failure mode may be higher, due to the cumulative effects of its occurrence.
- The mathematical formulation for the computation of the RPN lacks a complete scientific basis.

Further FMEA shortcomings, including methodologies to overcome some of these limitations are available in the abundant literature about the FMEA (Gilchrist 1993; Bowles and Peláez 1995; Ben-Daya and Raouf 1996; Braglia et al. 2003a, 2003b; Chin et al. 2009; Ekmekçioğlu and Kutlu 2012; Paciarotti et al. 2014; Haq et al. 2015; Liu 2016).

First applications of Fuzzy Set Theory in handling uncertainties (fuzziness, vagueness, imprecision, etc.) related to information data were introduced by Professor L. A. Zadeh in 1965 (Bai et al. 2006; Liu et al. 2013a; Liu 2016). Since then, The approach has been widely used in various sectors including industrial manufacturing, automatic control, automobile production, banks, libraries and academic education (Bai et al. 2006).

The overall procedure of conducting a fuzzy criticality assessment proposed by Zadeh consists of four important aspects, including the fuzzification process, fuzzy rule base, fuzzy inference process and defuzzification process. Based on experience and expert knowledge, membership functions of both the risk factors and RPN are derived and represented with linguistic variables. These membership functions express the degree of membership of an input to a particular fuzzy set. They are used to convert or fuzzify crisp numerical values of the risk factors (inputs) into linguistic terms (outputs) during the fuzzification process (Bowles and Peláez 1995; Bai et al. 2006). Having converted different crisp inputs linguistic variables, fuzzy rules are developed to describe the riskiness of the system for each combination of input variables (Bowles and Peláez 1995). Thus, formulated in linguistic terms rather than in numerical terms, fuzzy rules are often represented by a sequence of “IF-THEN”, expressing fuzzy conditional statements. Few examples among the 75 fuzzy rules developed during this study are displayed below:

Rule 1: IF severity is High and occurrence is Moderate and detection is Very High, THEN fuzzy risk priority number (FRPN) is Medium

Rule 2: IF severity is Very High and occurrence is Low and detection is High, THEN FRPN is Medium.

Interestingly, converting human expertise and knowledge into fuzzy rules by means of linguistic variables increase the expressiveness of the obtained rules-based linguistic variables in comparison to the simple RPN calculations (Bowles and Peláez 1995).

At the core of the fuzzy logic procedure, fuzzy Inference constitutes the "black box" of the method, where experience and experts' knowledge are converted into various fuzzy rules. Also, the resulting fuzzy inputs are evaluated in fuzzy inference engine. The inference engine uses previously well-defined rule bases, consisting of IF-THEN rules and fuzzy logic operations, to determine the level of riskiness of various failure modes. During the defuzzification, the fuzzy controller converts fuzzified output conclusions into real or classical output data that express the riskiness of the design (Bowles and Peláez 1995).

4 Case Study

The case study illustrates the applicability of the proposed approach to seven reinforced concrete navigation locks of the Main-Danube-Canal. Using available damage data, 13 causes of failure are identified, assessed and compared based on their FRPN. These causes of failure are organized into failures that may impair the load-carrying capacity, the serviceability and the durability of the infrastructure. Causes of failure that may lead to a loss of the load carrying capacity include:

- Fatigue-induced Deterioration,
- Damage to steel reinforcements (exposed, etc.),
- Inaccuracies in the load assumptions.

Failures that are likely to cause an impairment of the serviceability include:

- Cracks in reinforced concrete,
- Excessive deformations,
- Constructive deficiencies of horizontal & vertical sealings,
- Damaged concrete surface with moisture leakage,
- Mechanical stress (ship impact, etc.).

Failures that are likely to impede the durability include:

- Temperature-related cyclic loads,
- Cyclic freezing and thawing,

- Chemical & driving attack (e.g., AAR, etc.),
- Constructive deficiencies (concrete quality, etc.),
- Rearward moisture penetration.

It is however important to stress that one of the main objective within the EMS-WSV consists of identifying the causes of failure that may hinder the load-carrying capacity and to undertake corrective measures. Therefore, the priority ranking of the selected navigation locks is based on the three causes of failure that are likely to hinder their load-carrying capacity (see Fig. 3).

5 Discussion

A priority ranking for maintenance interventions of 7 navigation locks is established based on estimated values of the fuzzy RPN of the three main causes of failure associated with the loss of load carrying capacity. It is obvious that the locks Eibach, Bachhausen, Strullendorf, Kelheim, Eckersmühlen, Hilpoltstein are not exposed to fatigue induced deteriorations (see Fig. 3). It is however important to stress that a previous case of fatigue induced-deterioration was reported at the navigation lock Bamberg in 2003 (Fleischer et al. 2009). While the closure of the facility had severe economic consequences on the complete Main-Danube-Canal, important maintenance activities were necessary to remedy the incident. Thereafter, the structural safety of the rest of the 15 navigation locks of the MDK was systematically analysed (Fleischer et al. 2009).

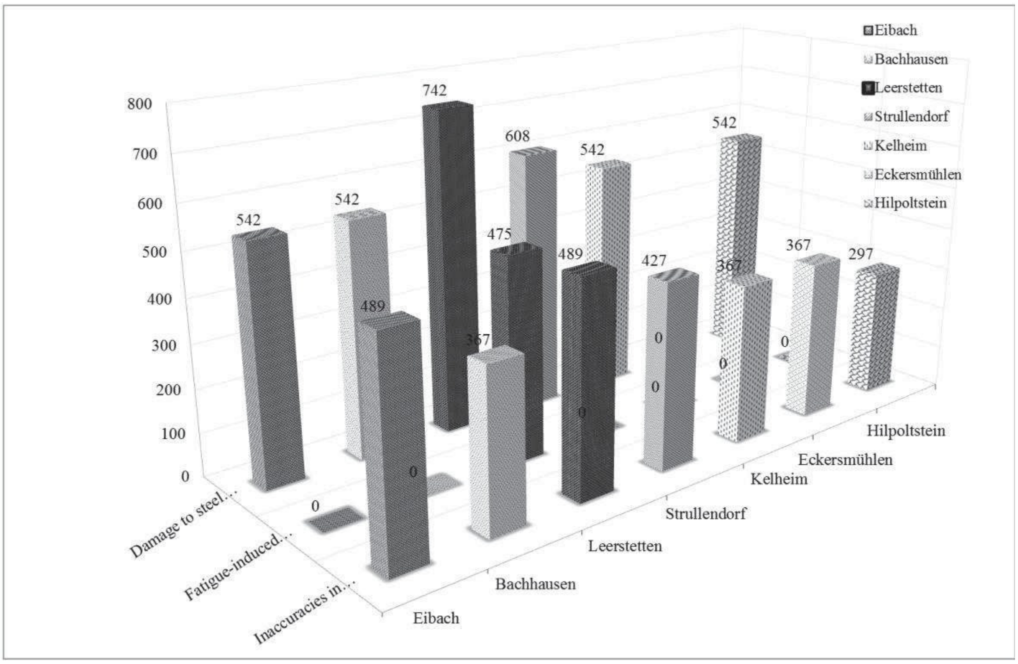

Figure 3: Fuzzy RPN of the three main causes that may lead to the loss of load carrying capacity of solid construction of reinforced concrete navigation locks

Even when these facilities are similar in terms of design and construction procedures, various damages are likely to occur with completely different intensity. More precisely, the three causes of failure are likely to have absolutely different effects on the load carrying capacity of the navigation locks

Eckermühlen, Hilpoltstein and Leerstetten. Hence, the extent of the maintenance interventions, required to mitigate the effects of these causes of failure, could significantly fluctuate from one asset to another. Equally important, it can be argued that the increasing level of complexity of the navigation locks in terms of design and construction processes may exacerbate various deterioration mechanisms.

With the exception of the navigation lock Eckersmühlen, the rest of the locks are exhibiting structural deficiencies associated with both damage to steel reinforcements (corrosion of steel reinforcements). Hence, the occurrence of the corrosion of the steel reinforcements could be exacerbated by cracks in concrete, insufficient concrete cover, moisture pathways, loss of alkalinity due to carbonation or chlorides. It should be mentioned that even though the design and construction procedures of navigation locks have significantly evolved during the last decades, inaccuracies associated with load assumptions remain issues of great concern. This can be explained by both changing loads and environmental conditions. Also, the normative codes for the design of the facility are not always updated.

Since the main focus of this study is to rank different navigation locks for maintenance interventions, it is assumed that fatigue induced deterioration is given the highest priority. Thus, the navigation lock Leerstetten with a fuzzy RPN of 475 is classified as main infrastructure to be considered for maintenance interventions. Regarding damage to steel reinforcements, the navigation lock Leerstetten with a fuzzy RPN of 742 was regarded as most critical asset. At the same time, the navigation lock Strullendorf with a fuzzy RPN of 608 could be ranked second, while the navigation locks Bachhausen, Eibach, Kelheim and Hilpoltstein with a fuzzy RPN of 542 were all portraying the same risk of loss of load carrying capacity due to damage to steel reinforcements. With respect to inaccuracies in load assumptions, the navigation locks Leerstetten and Strullendorf, respectively with fuzzy RPN of 489 and 427 were given the highest priority. Following a similar reasoning, the seven navigation locks could be ranked according to the effects of the three causes of failure on the load carrying capacity as follows: Leerstetten, Strullendorf, Eibach, Bachhausen, Kelheim, Hilpoltstein and Eckersmühlen.

6 Conclusion

In the present paper, a qualitative approach, namely the fuzzy FMEA, has been suggested to not only the effects of deterioration mechanisms on the structural reliability of waterway infrastructure assets, but also to assess their potential risk of failure. An assessment of damage data, collected during previous regular visual inspections revealed that fatigue induced-damages, corrosion of steel reinforcements and inaccuracies in load assumptions were the causes of failure that could hinder the load carrying capacity of these structures. Another outcome of the study is the hierarchical structuration of a waterway infrastructure asset. Indeed, main structural components of a navigation lock were ranked taking into account their contribution to the fulfilment of normative requirements. “Solid construction” and “steel construction” are the main object subcategories, whose deterioration may significantly hinder the structural reliability of these assets. However, other components, including “joint tapes”, “drives”, “corrosion protection” and “sealing elements” should also be granted a great attention.

This research have highlighted the possibility of using simple engineering qualitative approach to analyse damage data collected during regular visual inspections. In addition, based on experience and experts knowledge, key figures are developed and used to rank infrastructure assets for repair and maintenance interventions. However, a more integrated approach, for example a cost effective strategy for repair and maintenance interventions of the current backlogged maintenance of waterway infrastructure assets may necessitate the consideration of further risk factors (mean time for repair, spare parts, etc.). In addition, a combination of various multi criteria decision making methods, including the Analytical Hierarchy Process (AHP), Decision Making Technique for order preference by similarity to ideal solutions (TOPSIS), Decision making trial and evaluation laboratory (DEMATEL) should be envisaged in further approaches. This study is regarded as a significant step towards making a valuable use of passed inspections data and providing waterway infrastructure managers with addition key figures in decision making process about repair and maintenance interventions.

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