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Selection Strategy of Failure Modes for Repair and Maintenance Activities

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ABSTRACT

Strategic decision making about repair and maintenance activities is increasingly becoming a major concern in a context where navigational assets are aging and suffering various deterioration mechanisms, affecting their structural reliability. This paper examines the effects of various failure modes on the structural reliability of navigational assets and introduces priority weights that are used to rank different failure modes with respect to the ensuring riskiness of infrastructure failure. Based on previous findings of a qualitative as well as quantitative analysis of the emerging risk of infrastructure failure by means of the Failure Mode and Effects Analysis (FMEA), a Multi-Criteria Decision Making (MCDM) Method is used in this study to take into account not only the vagueness and subjectivity of expert knowledge, but also to take into consideration uncertainties of available damage data. In a previous study the Severity (S) of the consequences of a potential failure, probability of Occurrence (O) of the failure mode and probability of Detection (D) of the cause of the failure were identified as overriding criteria for assessing the emerging risk of infrastructure failure, using the Failure Mode and Effects Analysis (FMEA). Applying a Multi-Criteria Decision Making method (MCDM), namely the Analytic Hierarchy Process (AHP) to these criteria, priorities weights are developed to enhance decision making about repair and maintenance activities. Our findings revealed four categories of failure modes that can be summarized into failure modes that may hinder the durability of the infrastructure and failure modes that are likely to alter the structural reliability of the structure in a very short term. The proposed methodology also takes into account influential aspects of various failure modes as well as the subjectivity of expert judgments. This paper contributes to shed more light on how past damages data and expert knowledge can be combined to infer key figures that are useful for the identification of failure modes for repair and maintenance actions.

Keywords:

Maintenance and operation, Multi-Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP), Priority weights

1 Introduction

The sustainable economic growth, productivity, resilience and competitiveness of the German economy, in the prevailing context of repetitive economic crises as well as the well-being of the German population heavily depend on the reliability and durability of its infrastructure assets. Accordingly, German authorities, in charge of navigational assets own the responsibility of managing a network of facilities that meet its intended requirements of availability, operability, structural reliability and safety during the intended service lifetime. However, the heterogeneous portfolio of German navigational assets, including navigation locks, weirs, uplifts, sag pipes, bridges, etc. is faced with various deterioration processes, associated with aging factors and environmental stressors. Especially, the ongoing deterioration processes may impede the serviceability, the ultimate load-carrying capacity and the durability of the navigational assets. In addition to the structural degradation, failures of these infrastructures could pose the risk of secondary cascading effects, whose consequences may be far beyond a simple loss of service.

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Age might be regarded as an important factor that considerably impacts the structural reliability and functionality of these assets, and thus, fosters their vulnerability against threats posed by changing environmental conditions, insufficient maintenance activities. At the same time, deferred maintenance activities constitute huge burdens that urgently need to be addressed. More specifically, almost 30% of the navigation locks and weirs of the Waterways and Shipping Administration (WSV) were constructed prior to 1900. Beyond merely having already exceeded their designed service lifetime of about 100 years, some of these assets, which should have already be replaced are still in use, despite numerous deterioration processes, which may have significantly altered their structural reliability. While these facilities are aging and suffering various types of deterioration mechanisms, their level of service, structural reliability are decreasing and the potential risk of infrastructure failure is increasing. Likewise, several navigational assets that were built in the early 1960s, for instance at the Main-Danube-Canal, are exhibiting unexpected deterioration processes, which significantly affect not only their serviceability, but also their structural reliability. Although the renewal process of some of these infrastructures is engaged, it is important to acknowledge that design errors, inadequate and deferred maintenance are the main causes of this degradation.

Again, owing to restricted investment budgets and insufficient maintenance personnel, reinforced concrete and hydraulic steel structures of the German navigational assets have not been properly mended for decades. Yet, infrastructure serviceability highly depends on the frequency and quality of maintenance activities. Likewise, aging materials, insufficient maintenance and excessively prolonged service lifetime contribute to weaken these infrastructures, and thus, they become more vulnerable to otherwise environmental stressors. Because of the broad diversity of assets, the German Waterways and Shipping Administration (WSV) has since 2008 established a Maintenance Management System (EMS-WSV) to support decision-making process regarding the prioritization of repair and maintenance activities. As a result of the maintenance backlog, existing assets are deteriorating much faster than necessary and the well-established EMS-WSV is progressively reaching the limits of its capability.

This paper introduces a method to enhance decision-making with respect to prioritization various failure modes, identified in a Failure Mode and Effects Analysis (FMEA), taking into account the potential riskiness of failure modes concerning functional and structural requirements of an asset. The Analytic Hierarchy Process (AHP) developed in this study offers the chance of searching and evaluating the causal relationships between various criteria and failure modes. Furthermore, the proposed AHP can help to understand the absolute riskiness of individual failure modes in an overall perspective, and thus, to establish a priority order of failure modes for maintenance. A comparative analysis of several failure modes that affect reinforced concrete components of navigation locks is described in this paper to illustrate the procedure. The rest of the paper is structured as follows: section 2 presents a brief overview of the existing Maintenance Management System (EMS-WSV) of the WSV. Section 3 primarily describes the methodology used in developing our key figures and section 4 discusses a case study based on different failure modes, affecting reinforced concrete assets, to demonstrate the practical application and effectiveness of our proposed AHP.

2 Asset Inspection / Condition Assessment

2.1 Inspection procedure

Current decision-making strategies for repair and maintenance activities of navigational assets in Germany are based on analysis of damage data gathered during regular visual inspections. The definition of type of inspection, the extent and scale of execution of these inspections are characterized by a time-based approach. This is also in line with the structuration of navigational infrastructures that are clustered into two main categories: category A and category B. While assets of category A undergo Principal Inspections, Surveillance and Observation, assets of category B are just observed (BMVI, 2009). Principal inspections are carried out every 6 years with surveillance inspections at an intermediate period of 3 years. During principal inspections, the structural reliability, including the load-carrying capacity, the serviceability and durability of every single component of the asset is investigated by a certified civil engineer (BMVI, 2009). Hence, every distinct damage is gathered, evaluated and documented according to its effects on the structural requirements (structural reliability and serviceability) of the component and the asset as a whole.

The intended objective of principal inspections is to detect, evaluate ongoing deterioration processes and to make informed strategic decisions about the neediness and acuteness of repair, maintenance or potential replacement. Indeed, principal inspections are performed to determine the current condition of assets and identify prevailing structural deficiencies. For example, if evidence exists during an extensive inspection that a particular damage (crack, corrosion of the reinforcements, etc.) may impair the reliability/functionality of an asset, actions must be taken to prevent a complete failure of the component, and thereafter, avoiding a potential collapse of the asset.

During these in depth inspections, all gathered damages are rated on a scale from 1 to 4 (1 being good condition (CG_{gen}) and 4 being bad or “critical” condition). Using the Maintenance Management System “WSVPruf”, the overall condition grade of each infrastructure is generated, based on all collected damages. The decision-making about which component/asset should be maintained is largely governed by the overall condition grade of such components/assets.

2.2 Results of the current condition assessment procedure

Figure 1 compares the overall condition grade of navigation locks and weirs with the condition grade of various reinforced concrete components of these facilities.

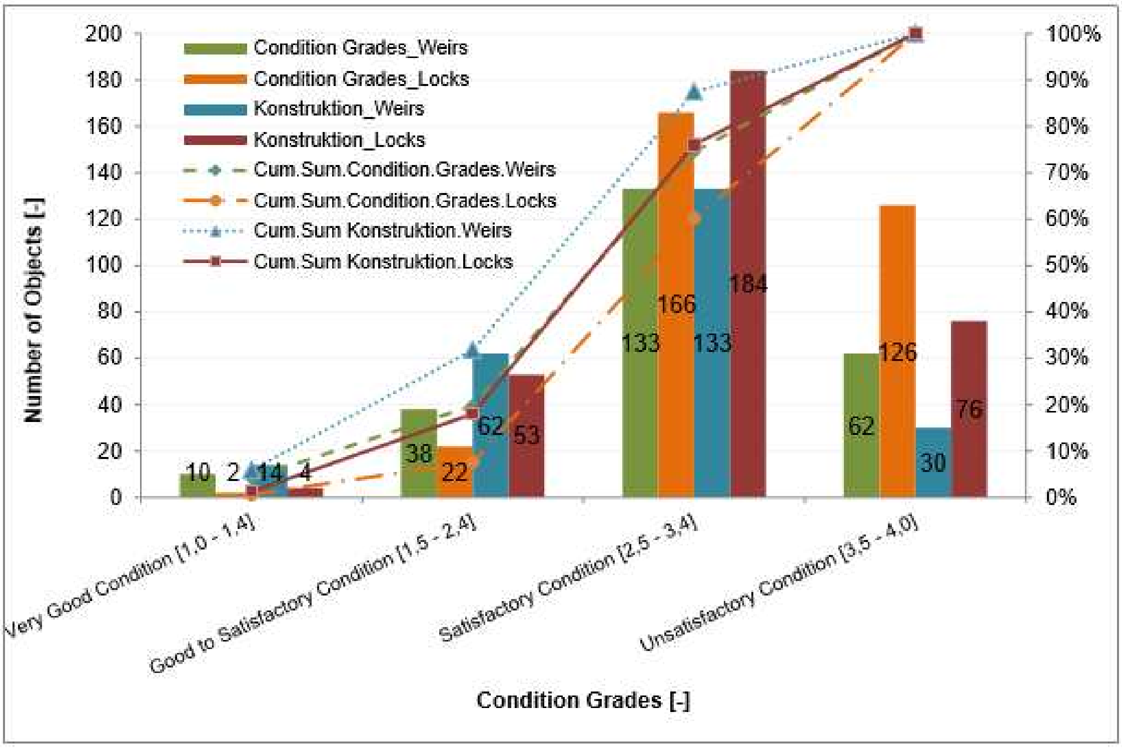

Figure 1: Condition grades distribution of whole assets and reinforced concrete structure "Konstuktion" for navigation locks and weirs in Germany (WSVPruf, 2018)

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It is apparent that the bulk of navigational assets (locks and weirs) are currently rated as having a either a satisfactory or an unsatisfactory condition. This in turn means that the load-carrying capacity, the serviceability and durability of these facilities may be threatened and that significant maintenance actions might be needed in a near future. More precisely, 33.54% and 12.55% of navigation locks and weirs respectively are already in a "critical" condition and suffer severe deterioration processes. This group of assets represents the current backlogged maintenance of the WSV that urgently needs to be addressed. In enhancing decision-making about infrastructure maintenance, the Federal Waterways Engineering and Research Institute (BAW) have since 2008 initiated within the framework of the EMS-WSV a forecasting model. Based on current condition grades, the BAW uses their forecasting model to predict the future condition of an asset. The main objective if the forecasting model is to estimate the probable remaining service lifetime of various aging infrastructures and to identify different assets, which owing to their actual condition, pose an eventual risk of infrastructure failure in a relatively near future.

2.3 Shortcomings of the current condition assessment approach

While the current overall condition grade merely expresses the neediness of undertaking repair/renewal measures, it does not explicitly take into account structural effects of damages on the structural reliability of the asset. Thus, a further differentiation between the large number of assets presently rated with a critical condition grade of 3.8 to 4 is not yet possible. Furthermore, uncertainties and subjectivity inherent to inspection procedures based on regular visual inspections as well as expert knowledge are not yet straightforward addressed in the decision-making procedure. Last but not least, the current condition grading system is in reality governed by a single worst damage, detected on the structure or component. Therefore, the influential and combined effects of a considerable amount of gathered damage data is currently not incorporated in the overall condition grade. Thus, their potential effects of the overall structural reliability of the infrastructure are not considered and their potential riskiness is simply ignored. Under these circumstances, the transparency, comprehensiveness and conclusiveness of the current decision-making process regarding repair and maintenance activities should be questioned and the emerging risk of infrastructure failure should also be integrated in the current condition grade.

3 Decision-Making based on Qualitative Risk Analysis

The growing technical complexity of large engineering systems and industrial products, together with the increasing public concern over their safety has stimulated the research and development of novel risk analysis and safety assessment procedures (Bhushan and Rai, 2004). However, modelling and analyzing complex risk scenarios increasingly require historical damage data as well as profound expert knowledge that are sufficiently expressive to be qualitatively as well as quantitatively analyzed. Besides, in risk assessment of large engineering systems, it may be difficult to employ probabilistic risk assessment approach in situations where data are mainly available in form of expert knowledge or qualitative information.

3.1 Making use of expert knowledge - Failure Mode and Effects Analysis (FMEA)

Initially developed in 1960s as formal design methodology in the aerospace industry for ensuring the structural reliability and safety requirements, the FMEA has been extensively adapted in various sectors, including automotive, nuclear, electronics, chemical and medical technologies (Gilchrist, 1993; Bertolini et al., 2004; Bowles, 2004; Liu, 2016). However, to the state of our knowledge, the method has not yet been explicitly employed to assess the structural reliability of civil engineering infrastructures. Likewise, various definitions of the FMEA, depending on pursued objectives, types of FMEA and field of implementation are available in the abundant literature. According to Stamatis (2003), the FMEA can be defined as "*an engineering technique used to define,*

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identify and eliminate known and/or potential failures, problems, errors and so on from the system, design, process, and/or service be-fore they reach the consumer." Similarly, Lui (2016) describes 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, design or services".

In essence, the FMEA heavily relies on expert knowledge, and thus, is considered as a qualitative risk assessment approach. The FMEA is supported by cause and effect chains, which are used to identify potential design and process failures of a system prior to their occurrence. In doing so, emerging risk of failures is minimized by either proposing design changes or by adjusting operational procedures whenever the aforementioned designed modifications cannot be formulated. As Lui (2016) pointed out, the main objective of the FMEA is to assist analysts in prioritizing failure modes of a system, design, process, product or service in order to adequately assign the limited resources to the highest risk items. Although a traditional FMEA can be summed up in a two-step procedure, namely the analysis of the system (Steps 1 to 3) and the risk assessment or criticality assessment (Step 4 & 5), the FMEA-implementation includes the following main steps:

- Step 1: delineation of the structure and components of the system to be analyzed;
- Step 2: definition of functions of the selected component, subsystem or system;
- Step 3: identification of failure modes and failure causes for each component as well as the effects of failure modes on components, subsystems and the entire system;
- Step 4: computation of the Risk Priority Number (RPN); depending on the RPN, rank and identify failure modes that urgently need to be maintained;
- Step 5: suggest improvement measures to mitigate the risk and enhance the system performance.

The definition of failure modes, failure causes and failure effects in a conventional FMEA depends on the level of analysis and the criteria used for the assessment of the risk of failure. Thus, the FMEA is regarded as a hierarchical modelling process aiming at constructing an attribute tree, which can either be achieved by using a top-down or a bottom-up approach. Accordingly, an essential task in analyzing a system or infrastructure asset is the hierarchically decomposition into its main components (see Panenka & Nyobeu, 2018b). One of the main ideas behind the structural decomposition of an asset into its main constituents is the necessity of identifying relevant components that significantly contribute to the fulfillment of structural and performance requirements. Also, during the hierarchical structuration of the asset, sub-functions as well as main functions of different components of an asset are identified and interfaces between various components are well established. Thus, having identified the essential components of an infrastructure, one can employ the FMEA to identify, evaluate and mitigate potential failure modes that may hinder the structural reliability of these components.

The FMEA provides both qualitative and quantitative measures to identify failures modes and assess their effects towards the quality/structural reliability of products/systems. In a conventional FMEA, the risk priorities of failure modes are determined through the Risk Priority Number (RPN), which is the product of the probability of occurrence or the frequency of a failure mode (O), the probability of detecting a failure before the realization of it impact (D) and the Severity or seriousness of the effects of the failure mode (S) (see Figure 2).

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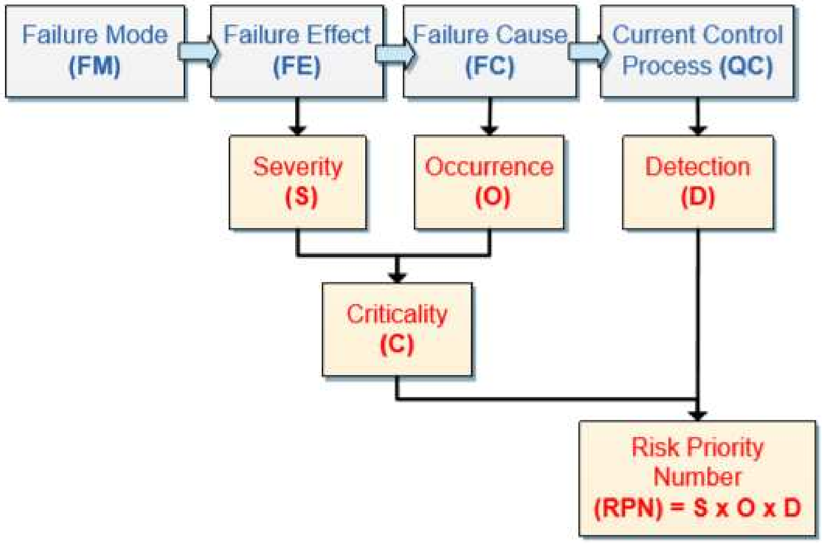

Figure 2: Cause-Effect Chain in a traditional FMEA

It is also important to stress that additional relevant risk criteria, including economical aspects, safety, equipment/system importance, maintenance cost, failure rate, mean repair time and operation condition are not often considered in analyzing the risk of failure. Thus, the RPN is computed by assigning to the three selected risk criteria values ranging from 1 to 10. This results in RPN ranging from 1 to 1000, with higher RPNs being assumed to pose a greater risk of structural failure than lower RPNs (Lui, 2016).

3.2 Enhancing the risk prioritization through Analytical Hierarchy Process (AHP)

Although the FMEA may capture the decision maker´s intuition, judgment and experience, one of the main shortcomings is its indifference to the subjective impression that one failure mode (FM) or risk factor may be of great importance for the risk assessment than others. This subjective judgment is not yet sufficiently taken into account by the RPN, computed in the traditional way by merely multiplying the values of the three risk factors O, S and D. To strengthen the risk assessment procedure and enhance the capability of the conventional FMEA by considering these potential relationships among various causes of failure or risk criteria (i.e. O, S and D), the Analytical Hierarchy Process (AHP), initially developed by Saaty in 1980 (Saaty, 2008) is used in this study. Instead of assessing each FM by separately determining the RPN, the AHP is used to determine the influential weights of each Failure Mode, and thus, various failure modes can be prioritized accordingly.

The AHP is a powerful and flexible multi-criteria decision-making tool that hierarchically decomposes a challenging decision problem into different levels of decision, where both qualitative and quantitative aspects are considered. It also combines both subjective and objective judgments into an integrative framework based on ratio scales from simple pairwise comparisons and assist the analyst to organize the critical aspects of a problem into a hierarchical structure (Saaty, 1990 & 2008). Similarly, Saaty (1987) describes the AHP as "*a nonlinear framework for carrying out both deductive and inductive thinking without use of the syllogism by taking several factors into consideration simultaneously and allowing for dependence and for feedback, and making numerical trade-offs to arrive at a synthesis or conclusion*." Because significant failures are usually caused by combinations of two or more failure modes, the AHP is employed to determine the influential weights of various failure modes and prioritize the failure modes accordingly. While the AHP employs a unidirectional hierarchical relationship among decision levels, interdependence among various components of the system is also considered and composite priority weights are generated through the development of a "super-matrix" (Saaty, 2008). The AHP is a three step process, which hierarchically breaks down a complex problem. Within this hierarchical structure, the overall decision objective lies at the top of the hierarchical inverse tree, various criteria, sub-criteria are arranged on the next level below the main goal and decision alternatives are displayed at the tail of the hierarchy. Decision makers then compare each factor to all other factors at the same level of hierarchy using a pairwise comparison matrix to find their local priority weights or relative importance. The optimal solution is the alternative with the greatest cumulative weight (Saaty, 1990). It is however essential to note that the adjective "relative" is used in this context because the obtained criteria priorities are evaluated with respect to each other.

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3.3 The proposed FMEA-AHP methodology

Aiming at enhancing the expressiveness of the current condition grade within the EMS-WSV, the proposed methodology is used not only to establish influential relationship between structural system requirements and possible risks of a system failure, but also to generate additional key figures, which may support the development of joint maintenance and expansion strategies (See Figure 3, Panenka and Nyobeu, 2018b).

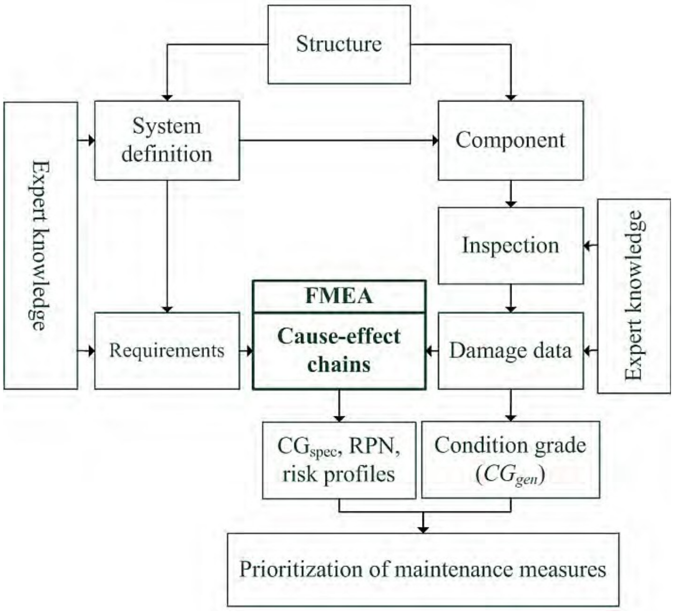

Figure 3: Implementation of FMEA in the condition assessment of navigational assets (Panenka & Nyobeu, 2018b)

Decision-making process can be considered as the choice, on some basis or criteria, of one alternative among a set of alternatives. Hence, a rational decision-making must be made on the basis of multiple criteria rather than a single criterion. This requires the assessment of various criteria and the evaluation of alternatives on the basis of each criterion and then the aggregation of these evaluations to achieve an overall relative ranking of the alternatives with respect to the pursued objective. Saaty (2008) has clearly recognized the inescapable necessity of making decisions based on several criteria and suggested that "*to make a decision, we need to know the problem, the need and purpose of the decision, the criteria of the decision, their sub-criteria, stakeholders and groups affected and the alternative actions to take*". Again, Saaty (2008) contended that when trying to determine the best alternative or in the case of resource allocation, the appropriate share of limited resources must be supported by priorities for various alternatives. More specifically, if the main goal of our maintenance management strategy is to rank various failure modes for maintenance activities, the risk criteria/factors of the FMEA could be regarded as assessment criteria and the identified failure modes as various alternatives Thus, the decision of ranking several failure modes for repair and maintenance activities is decomposed into a multi-level hierarchic structure with the main objective at the top of the hierarchy, the decision criteria in the middle and the identified alternatives at the tail of the hierarchy (See Figure 4).

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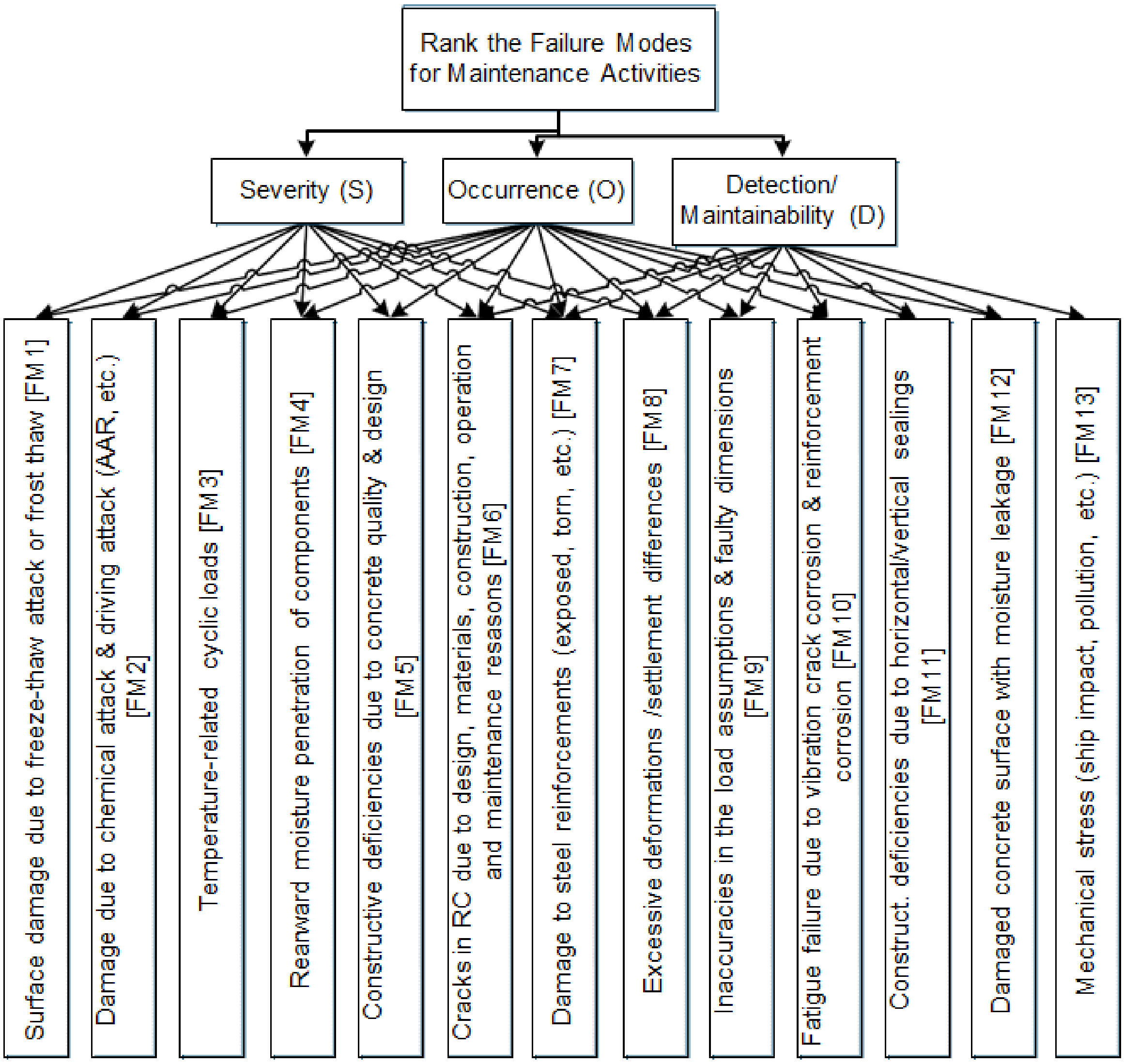

Figure 4: Decision hierarchy for ranking failure modes for repair and maintenance activities

In this context, a structured decision making procedure for the generation of overall priorities for alternatives can only be completed through the decomposition of the decision into the following steps.

a) Perform a FMEA in order to identify the potential failure modes;

b) Establishment of a hierarchy structure. The decision making process describing the problem to be solved, is decomposed into a hierarchy of goals, criteria sub-criteria and alternatives (i.e. failure modes). This is also called decision modelling and simply consists of building a hierarchy to analyze the decision (see Figure 4);

c) Construction of a set of pairwise comparison matrices for preference analysis. The relative importance of the criteria is pairwise compared with respect to the designed goal to derive relative priority weights for various criteria. The consistency of judgments is assessed to ensure that a reasonable level of consistency in terms of proportionality and transitivity is reached. Because the relative importance or weight of each criterion may differ from one to another, the relative priority of each criterion is derived through pairwise comparisons, using a numerical comparison scale, introduced by Saaty (1987) (See Table 2).

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Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgement numerically because there is no good word to describe it.
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A comparison mandates by choosing the smaller element as the unit to estimate the larger one as a multiple of that unit
Rationals	Rations arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix
1.1 – 1.9	For tied activities	When elements are close and nearly indistinguishable; moderate is 1.3 and extreme is 1.9.

Table 1: Evaluation scale of relative preference for pairwise comparisons (Saaty, 2008)

d) Derive local priorities or relative preferences for the alternatives. Using the Saaty´s pairwise comparison scale, local priorities for alternatives are derived with respect to each criterion separately (following a similar process as in the previous step, i.e., compare the alternative pairwise with respect to each criterion). Once again the consistency of experts´ judgments is checked and adjusted if necessary.

e) Derive overall Priorities or weights for the criteria (Model Synthesis). Various alternative priorities, obtained during previous analysis are aggregated to generate a weighted sum that takes into account the weight of each criterion and establishes the overall priorities of the alternatives. Then, identify the alternative with the highest overall priority, which constitutes the most critical issue or the preferential choice for repair and maintenance activities.

f) Perform Sensitivity analysis. A study of how changes in the weights of the most influential criterion could affect the overall priority weights of various alternatives is done to understand the rationale behind the obtained results.

g) Making a final decision. Based on the synthesis results and sensitivity analysis, a decision can be made.

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4 Case Study

4.1 Assigning Priorities through Pairwise Comparisons

Waterway maintenance practitioners are faced with numerous questions, including what are the main failure modes that are likely to threaten the structural reliability of a navigational asset. They are also concerned with the influential relationship between these various failure modes. Thus, their prime objective is to establish a condition-risk-based maintenance strategy, which can be best used to address the huge burden of backlogged maintenance. Therefore, the case study discussed in this paper is an application of the AHP to solve the thorny problem of evaluating risk priorities of various failure modes and sharpening the focus on most pressing issues, in terms of their impact on the structural reliability of the asset, for maintenance activities. When selecting the most acute failure modes that urgently need to be maintained, the Severity (S) of the consequences of the failure mode, the probability of occurrence (O) as well as detection (D) of the failure mode are the main decision criteria to be considered. These criteria must be compared in order to derive their relative priorities (weights), and thus, determine their relative importance in meeting the overall goal of ranking various failure modes for maintenance.

Using the fundamental scale, comparisons that reflect the relative strength of preferences and feelings are made to construct the kernels of Fredholm operators from which ratio scales are derived in the form of principal eigenvectors or eigenfunctions (Saaty, 1987 and Saaty, 1990). These comparisons are fundamental in the use of AHP. We must first establish the relative priority of each of the three criteria by judging them in pairs for their relative importance, thus generating a pairwise comparison matrix. Judgments, which are represented by numbers from the fundamental scale, are employed to make the comparisons.

Examining the matrices below (see Table 2), one can note that a pair of elements (*ij*) in a level of the hierarchy are compared with respect to parent element in the level immediately above as a common property or criterion used to judge as to which one has it more and by how much. The typical way to phrase a question to fill an entry in the matrix of comparisons is: when considering two elements, *i* on the left side of the matrix and *j* on the top, which one contributes the most to the fulfillment of the overall goal, in other words, which one is considered more important in achieving the goal, described by the decision problem and up to what value (using the fundamental scale values from table 1)?. This gives us *aij* (or *aji*). The reciprocal value is then automatically entered for the transpose. The question asked in making a pairwise comparison can influence the judgments provided, and hence, also the priorities (see Table 2).

4.2 Assessment of various criteria/Deriving Priorities (Weights) for the Criteria

The importance of various risk criteria is pairwise compared with respect to the desired goal of deriving their relative priority weights (see Table 2). Since the proportion of inconsistency CR = 0.0036 is less than 0.1, we can assume that our judgments matrix is reasonably consistent.

	Severity (S)	Occurrence (O)	Detection (D) / Maintainability	**Normalised Priorities (Weights)**	**Idealised Priorities (Weights)**
Severity (**S**)	1	3	5	**0.6479**	**100 %**
Occurrence (**O**)	1/3	1	2	**0.2299**	**35.48 %**
Detection (**D**)	1/5	1/2	1	**0.1222**	**18.86 %**
λ_{max} = 3.004	**CI = 0.0018**		**CR = 0.0036**		

Table 2: Pairwise comparison matrix for decision criteria with respect to main objective

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The normalized priorities may also be expressed in the ideal form by dividing each priority by the largest one, 0.6479 for Severity of the consequences of a failure. Basically, these results also indicate that the severity has 64.79% of the overall importance of the criteria, followed by the occurrence with 22.99% and detection (12.22%) respectively. Subsequently, the criteria Severity of consequences of various failure modes is regarded as the most important criteria in ranking various failure modes for repair and maintenance activities and the proportionate value of the occurrence and detection can then be estimated. The results of this criteria assessment clearly show that the probability of occurrence of the cause a failure is about 35.48% as good as the severity of its effects and the probability of a potential failure mode being detected is about 18.86% as good as the severity of its consequences.

4.3 Deriving Local Priorities (Preferences) for the Alternatives: Evaluation of alternatives on the basis of the assessed criteria

The next step consists of setting up comparison matrices for various failure modes (alternatives), which are compared with respect to each of the identified criterion. Since the derived priorities are valid only with respect to each specific criterion, they are often called local priorities. Thus, three more pairwise comparison matrices are generated to derive local priorities for each alternative based on the judged importance of one alternative over another with respect to a common criterion.

Severity	FM1	FM2	FM3	FM4	FM5	FM6	FM7	FM8	FM9	FM10	FM11	FM12	FM13	**Priority Vectors (Weights)**	**Rank**
FM1	1	2	3	3	1/3	1/7	1/7	1/5	2	1/3	3	2	3	**0.05785**	**7**
FM2	1/2	1	1/2	2	1/3	1/6	1/6	1/3	1/5	1/5	1/2	2	3	**0.02804**	**10**
FM3	1/3	2	1	3	1/2	1/5	1/5	1/3	1/3	1/3	2	2	4	**0.04144**	**8**
FM4	1/3	1/2	1/3	1	1/5	1/8	1/8	1/5	1/5	1/5	1/2	2	2	**0.02036**	**11**
FM5	3	3	2	5	1	1/3	1/3	3	1/3	3	3	5	7	**0.10159**	**4**
FM6	7	6	5	8	3	1	1/2	3	3	3	5	7	8	**0.18428**	**2**
FM7	7	6	5	8	3	2	1	3	3	2	5	8	8	**0.20406**	**1**
FM8	5	3	3	5	1/3	1/3	1/3	1	1/3	1/3	3	5	5	**0.07988**	**6**
FM9	1/2	5	3	5	3	1/3	1/3	3	1	3	5	5	7	**0.12346**	**3**
FM10	3	5	3	5	1/3	1/3	1/2	3	1/3	1	3	5	5	**0.09419**	**5**
FM11	1/3	2	1/2	2	1/3	1/5	1/5	1/3	1/5	1/3	1	2	2	**0.03139**	**9**
FM12	1/2	1/2	1/2	1/2	1/5	1/7	1/8	1/5	1/5	1/5	1/2	1	2	**0.01907**	**12**
FM13	1/3	1/3	1/4	1/2	1/7	1/8	1/8	1/5	1/7	1/5	1/2	1/2	1	**0.0144**	**13**
					λ_{max}= 14.4037				**CI = 0.11698**			**CR = 0.07499**			

Table 3: Pairwise comparison of alternatives with respect to the criterion Severity

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The consistency test (CR = 0.07499 < 0.1) clearly shows that subjective judgments made during pairwise comparisons, are fairly consistency. Thus, the judgment matrix and the computed priority weights are quite reliable. Also, as it can be seen from the Table 4 (two right-most columns), the priorities for the identified failure modes with respect the severity of their effects, and thereafter, their respective contribution to the non-compliance with the design requirements of the system are computed. With priorities weights of 0.204, 0.184, 0.123, corrosion of steel reinforcements (**FM7**), reinforced concrete cracks (**FM6**) and inaccuracies in load assumptions and faulty dimensions (**FM9**) are respectively the three main failure modes, whose consequences can be detrimental to the structural reliability of the system. Likewise, comparison of various failure modes with respect to the probability of occurrence of the causes of potential failure modes as well as the probability of the failure being detected are displayed in the following tables 4 and 5.

Occurrence	FM1	FM2	FM3	FM4	FM5	FM6	FM7	FM8	FM9	FM10	FM11	FM12	FM13	**Priority Vectors (Weights)**	**Rank**
FM1	1	2	3	3	3	1/2	1/2	5	5	8	1/2	1/2	2	**0.09828**	**4**
FM2	1/2	1	3	3	1/3	1/3	3	3	4	6	1/2	1/2	2	**0.08912**	**6**
FM3	1/3	1/3	1	3	2	1/3	1/4	3	3	7	1/3	1/3	2	**0.05993**	**8**
FM4	1/3	1/3	1/3	1	1/3	1/3	1/3	2	2	2	1/2	1/8	1/3	**0.02945**	**10**
FM5	1/3	3	1/2	3	1	1/3	1/4	4	3	5	1/3	1/3	2	**0.06749**	**7**
FM6	2	3	3	3	3	1	2	6	8	8	3	1/3	3	**0.14795**	**2**
FM7	2	1/3	4	3	4	1/2	1	5	5	8	3	1/2	2	**0.12121**	**3**
FM8	1/5	1/3	1/3	1/2	1/4	1/6	1/5	1	2	2	1/4	1/8	1/3	**0.02131**	**11**
FM9	1/5	1/4	1/3	1/2	1/3	1/8	1/5	1/2	1	3	1/4	1/7	1/3	**0.01967**	**12**
FM10	1/8	1/6	1/7	1/2	1/5	1/8	1/8	1/2	1/3	1	1/7	1/8	1/5	**0.01235**	**13**
FM11	2	2	3	2	3	1/3	1/3	4	4	7	1	1/2	1/2	**0.09191**	**5**
FM12	2	2	3	8	3	3	2	8	7	8	2	1	3	**0.18193**	**1**
FM13	1/2	1/2	1/2	3	1/2	1/3	1/2	3	3	5	2	1/3	1	**0.05941**	**9**

λ_{max}= 14.4772 **CI = 0.1231** **CR = 0.07891**

Table 4: Pairwise comparison matrix of alternatives with respect to the criterion Occurrence

Detection	FM1	FM2	FM3	FM4	FM5	FM6	FM7	FM8	FM9	FM10	FM11	FM12	FM13	**Priority Vectors (Weights)**	**Rank**
FM1	1	3	5	3	1/3	1/3	1/3	3	5	5	3	1/3	1/3	**0.07606**	**6**
FM2	1/3	1	3	3	1/3	1/4	1/3	1/3	3	3	1/3	1/4	1/5	**0.03677**	**9**
FM3	1/5	1/3	1	1/2	1/3	1/6	1/5	1/3	2	1/2	1/5	1/8	1/8	**0.01801**	**12**
FM4	1/3	1/3	2	1	1/3	1/6	1/4	1/3	1/2	3	1/3	1/6	1/8	**0.02307**	**10**
FM5	3	3	3	3	1	1/2	1/2	4	6	8	3	2	1/2	**0.11743**	**4**
FM6	3	4	6	6	2	1	3	4	8	8	3	1/4	1/2	**0.14141**	**3**
FM7	3	3	5	4	2	1/3	1	3	5	8	1/3	1/2	1/2	**0.10125**	**5**
FM8	1/3	3	3	3	1/4	1/4	1/3	1	3	4	2	1/3	1/3	**0.05414**	**8**
FM9	1/5	1/3	1/2	2	1/6	1/8	1/5	1/3	1	2	1/3	1/7	1/8	**0.01937**	**11**
FM10	1/5	1/3	2	1/3	1/8	1/8	1/8	1/4	1/2	1	1/4	1/8	1/8	**0.0151**	**13**
FM11	1/3	3	5	3	1/3	1/3	3	1/5	3	4	1	1/3	1/3	**0.06836**	**7**
FM12	3	4	8	6	1/2	4	2	3	7	8	3	1	1/2	**0.15362**	**2**
FM13	3	5	8	8	2	2	2	3	8	8	3	2	1	**0.17541**	**1**

λ_{max}= 14.5436 **CI = 0.12863** **CR = 0.08246**

Table 5: Pairwise comparison matrix of alternatives with respect to the criterion Detection

The results of the pairwise comparisons with respect to the occurrence and detection are entered in a reciprocal comparison matrix as shown in Tables 4 and 5. With values of the consistency ratio estimated at 0.07891 and 0.08246 respectively for the criteria occurrence and detection, it can be undoubtedly inferred that these judgment matrices are consistent enough. It is however important to highlight that the failure modes **FM12, FM6, FM7** and **FM1** are the main deterioration processes that affect the structural reliability of reinforced concrete navigational assets. On the other hand, failure modes **FM13, FM12**, **FM6**, **FM5** and **FM7** can be easily detected, in comparison to failure modes **FM10**, **FM3** and **FM9** that are difficult to detect, and whose consequences are likely to significantly alter the structural reliability of the asset.

4.4 Model Synthesis: Aggregation of the local priorities to derive overall priorities of alternatives with respect to the problem to be solved

To determine the final priorities of various failure modes with respect to the main goal of the present study, which consists of ranking failure modes for repair and maintenance activities, individual judgments, made at the risk criteria and alternatives levels must be aggregated. Thus, a synthesis of various analyses is carried out by multiplying each ranking by the priority of its criterion or subcriterion and adding the resulting weights for each alternative to obtain the final priorities of the 13 failure modes. In other words, to aggregate the local priorities of the 13 failure modes, an aggregated matrix is developed by calculating the arithmetic mean according to Forman and Peniwati (1998) (See Table 6 below).

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	Severity	**Occurrence**	**Detection**	**Global Priority Weights**	**Rank**
Criteria Priority Weights (CW)	**0.6479**	**0.2299**			
Surface damage due to repeated cycles of freezing and thawing **(FM1)**	0.05785	0.09828	0.07606	**0.069**	**6**
Damage due to chemical attack & driving attack (e.g., AAR, etc.) **(FM2)**	0.02804	0.08912	0.03677	**0.043**	**11**
Temperature-related cyclic loads **(FM3)**	0.04144	0.05993	0.01801	**0.043**	**12**
Rearward moisture penetration of components **(FM4)**	0.02036	0.02945	0.02307	**0.023**	**13**
Constructive deficiencies associated with concrete quality & concrete design methodology **(FM5)**	0.010159	0.06749	0.11743	**0.096**	**3**
Cracks in RC due to design, materials, construction, operation and maintenance reasons **(FM6)**	0.18428	0.14795	0.14141	**0.171**	**2**
Corrosion of steel reinforcements (exposed, torn, etc.) **(FM7)**	0.20406	0.12121	0.10125	**0.172**	**1**
Excessive deformations /settlement differences **(FM8)**	0.07988	0.02131	0.05414	**0.063**	**8**
Inaccuracies in the load assumptions & faulty dimensions **(FM9)**	0.12346	0.01967	0.01937	**0.087.**	**4**
Fatigue due to vibration cracks & corrosion of embedded steel reinforcements **(FM10)**	0.09419	0.01235	0.0151	**0.066**	**7**
Constructive deficiencies associated with horizontal and vertical sealings **(FM11)**	0.03139	0.09191	0.06836	**0.05**	**9**
Damaged concrete surface with moisture leakage **(FM12)**	0.01907	0.18193	0.15362	**0.073**	**5**
Mechanical stress (ship impact, pollution, etc.) **(FM13)**	0.0144	0.05941	0.17541	**0.044**	**10**
	Overall CR of the hierarchy = 0.05849				

Table 6: Synthesis of the model priorities

With an overall inconsistency ratio (CR) of about 0.05849 < 0.1, the correctness and the consistency of the given pairwise comparisons is quite satisfactory. Based on the calculation of these overall/combined priority weights, different alternatives (failure modes) can be sorted according to their weight values, as shown in table 6. The analysis of the overall priority weights puts in evidence that reinforced concrete cracks and corrosion of steel reinforcements are the main deterioration processes that have significant effects on the structural requirements of navigational assets. It can also be noted that construction deficiencies, associated with concrete quality and design methodology must be given a great consideration in the design and construction phase, in order to avoid their further consequences that are likely to substantially alter the durability of assets.

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4.5 Sensitivity Analysis

In many areas where the optimization of processes or systems is granted a great consideration, the question of sensitivity of results has always been at the centre of concern. Sensitivity analysis enables decision makers to improve the credibility of their analytical model by providing appropriate answers to “*what if*” questions and by quantifying the robustness of the optimal solution under variations in the problem parameters (Erkut and Tarimcilar, 1991). The specific objective of the sensitivity analysis is to check whether few changes in the judgment evaluations may result to significant modifications in the overall priority ranking. Thus, sensitivity analysis is used to investigate the robustness of the overall priority weights of alternatives to changes in the priorities of the criteria at the level immediately below the main goal of the analysis.

More specifically, although the criteria assessment undoubtedly suggests that the “severity” is the most important criteria (see Table 2) in ranking various failure modes, the overall ranking of alternatives is likely to change in accordance with shifts in analyst logic. Basically, each criterion is characterized by an important degree of sensitivity, i.e. the ranking of all alternatives may change dramatically over the entire weight range (Erkut and Tarimcilar, 1991). Therefore, by changing the priority weights (relative importance) of various criteria, a series of sensitivity analysis can be performed to explore the robustness of the current solution to potential shifts. However, it is important to stress that the sensitivity analysis, proposed in this paper is only relevant to the priorities of the three criteria, selected in this study. Also, in answering the following questions, different scenarios are simulated:

- what if the priority weights of various criteria are given the same value?
- what would be the best alternative if the relative importance of a single criterion is changed?

In assessing the impact of the change of a single criterion on the overall ranking of alternatives, only the “main effects” must be considered, as suggested by Bevilacqua and Braglia (2000). In other words, “interaction effects” of the changes made to the other two weights are ignored. This simplification is introduced by Bevilacqua and Braglia (2000), who contended that the final solution was mainly sensitive to changes in the priorities at the highest level of the hierarchy. Moreover, it is assumed that the AHP is used as a decision-making tool and that the decision maker is merely interested in ranking various alternatives. Hence, we are especially interested in the sensitivity of the alternative with the highest ranking.

4.5.1 Assigning the same value to the priority weights of the three criteria

Table 7 shows the results of the sensitivity analysis, based on the main assumption that the three criteria have the same relative importance and are assigned the same priority weight of 1/3. This consideration also leads to a reduction of about 50% of the relative importance of the criterion severity. It can also be observed that by adopting large changes of the weights of the first criteria it is possible to substantially alter the overall priority weights and the final ranking of several alternatives (**FM8, FM10, FM12 and FM13**). In addition, the initial ranking between the alternatives is not preserved, although reinforced concrete cracks and corrosion of steel reinforcements remain the relevant failure modes. Also, a shift of about 17% is observed between the initial priority weight of the failure mode **FM7** (0.172) and the current value of 0.1422.

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	Severity (S)	Occurrence (O)	Detection (D) /Maintainability	**Priority Weights**	**Rank**
CW	**0.3333**	**0.3333**	**0.3333**		
FM1	0.0579	0.0983	0.0761	**0.0774**	**6**
FM2	0.0280	0.0891	0.0368	**0.0513**	**10**
FM3	0.0414	0.0600	0.0180	**0.0398**	**12**
FM4	0.0204	0.0295	0.0231	**0.0243**	**13**
FM5	0.0102	0.0675	0.1174	**0.0955**	**4**
FM6	0.1843	0.1480	0.1414	**0.1579**	**1**
FM7	0.2041	0.1212	0.1013	**0.1422**	**2**
FM8	0.0799	0.0213	0.0541	**0.0518**	**9**
FM9	0.1235	0.0197	0.0194	**0.0542**	**8**
FM10	0.0942	0.0124	0.0151	**0.0405**	**11**
FM11	0.0314	0.0920	0.0684	**0.0639**	**7**
FM12	0.0191	0.1820	0.1536	**0.1182**	**3**
FM13	0.0144	0.0594	0.1754	**0.0831**	**5**

Table 7: Scenario 1: same value for the priority weights of the three criteria

4.5.2 Adopting different values for the priority weights of the three criteria

Similarly, the table 8 below illustrates the outcome of the sensitivity test, taking into account a reduction of about 25% of the initial value of the priority weight of the severity to 0.4859. It is apparent from these analyses that the values of the overall priority weights of various failure modes are affected by a change of about 5 to 8% of their initial values. More importantly, it can be seen that the rank of various failure modes (**FM2, FM3, FM4, FM5 and FM11**) has not been affected by the modification of the initial weight of the criteria severity. On the other hand, cracks in reinforced concrete, damages to steel reinforcements and Construction deficiencies in relation to concrete quality and concrete design methodology remain the essential failure modes that must be prioritized for maintenance activities.

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	Severity (S)	Occurrence (O)	Detection (D) /Maintainability	**Priority Weights**	**Rank**
CW	**0.4859**	**0.257**	**0.257**		
FM1	0.0579	0.0983	0.0761	**0.0729**	**5**
FM2	0.0280	0.0891	0.0368	**0.046**	**11**
FM3	0.0414	0.0600	0.0180	**0.0402**	**12**
FM4	0.0204	0.0295	0.0231	**0.0234**	**13**
FM5	0.0102	0.0675	0.1174	**0.0969**	**3**
FM6	0.1843	0.1480	0.1414	**0.1639**	**1**
FM7	0.2041	0.1212	0.1013	**0.1563**	**2**
FM8	0.0799	0.0213	0.0541	**0.0582**	**8**
FM9	0.1235	0.0197	0.0194	**0.070**	**6**
FM10	0.0942	0.0124	0.0151	**0.0528**	**10**
FM11	0.0314	0.0920	0.0684	**0.0564**	**9**
FM12	0.0191	0.1820	0.1536	**0.0955**	**4**
FM13	0.0144	0.0594	0.1754	**0.0674**	**7**

Table 8: Different values for the priority weights of the three criteria

As one can see, only by adopting large changes of the weights of the criterion severity, it becomes possible to significantly alter the values of the priority weights of various failure modes, although a reduction of the main criterion severity of about 25% results in a shift of the first position in final ranking of different alternatives. These findings clearly show an intrinsic robustness of the final priority weights, developed by means of the AHP method, considering sensitivity of the final ranking of alternatives to changes in the weights of the criteria in the second level of the decision hierarchy.

5 Discussion and Conclusion

This paper presents a methodology for ranking various failure modes and selecting most crucial failures that could alter the structural reliability of a navigational asset for repair and maintenance activities. In a context where German waterway infrastructure are ageing and faced with various deterioration mechanisms, the emerging risk of infrastructure failure is increasingly becoming an issue of great concern. Therefore, a rational decision making about repair and maintenance activities, supported by key figures describing the structural effects of various degradation mechanisms on the structural reliability of assets, is a foremost imperative. In addition, maintenance practitioners are often confronted during cyclic visual inspections with challenging decision making about which failure modes are likely to undermine the structural reliability of the asset. Yet, risk assessment techniques play a vital role in maintenance decision making given that these techniques can be used to systematically identify, analyze, evaluate current deterioration mechanisms and mitigate their potential risks with respect to the consequences of an infrastructure failure. Using the Analytical Hierarchy Process, primarily developed by Saaty (1990), priority weights for ranking various failure modes are derived based on various criteria of the Failure Mode and Effects Analysis (FMEA) and taking into account uncertainties, associated with the subjectivity of expert knowledge. In comparison to other traditional methods of solving the MCDM problem, the proposed methodology does not only assess multi-criteria decision problems in a more objective way by avoiding subjective effects on the priority weights, but it simultaneously serves for qualitative and quantitative analysis of available data. The ranking of priority weights of various failure modes, obtained from the FMEA-AHP-model is depicted in Table 8 as follows: **FM6 > FM7 > FM5 > FM12 > FM1 > FM9 > FM13 > FM8 > FM11 > FM10 > FM2 > FM3 > FM4**. Also, the findings of this study have highlighted the existence of four main categories of failure modes (See Figure 5). The first category that include the failure modes **FM1, FM2, FM3** and **FM4** with a relatively moderate probability of occurrence, which are easily detected and whose consequences may not have further incidence on the structural reliability of the asset. While immediate consequences of these categories of failures on the structural reliability of an asset are very limited, their long term effects are likely to hinder the durability of an asset.

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The second category consists of failure modes with a very high probability of occurrence, which are likely to be very easily detected and whose may have severe and unbearable consequences for the structural reliability of the facility. Including the failure modes **FM5**, **FM6** and **FM7**, this second group represents the main challenges that are facing maintenance practitioners and that urgently need to be addressed because of their effects on the load-carrying capacity of the structure. The third category of failure modes merely consists of failures **FM8**, **FM9**, and **FM10** with a very low probability of occurrence, which are often very difficult to detect and whose consequences can be detrimental to the structural reliability of the asset. The fourth category is composed of failure modes **FM11**, **FM12** and **FM13** with a very high probability of occurrence, which can be very easily detected and whose consequences are relatively low. These failures are more likely to have long term effects on the durability of the infrastructure. From the perspective of combined effects of various failure modes, it is however important to stress that long term effects failure modes of the first and fourth categories may inevitably lead to the loss of the structural reliability of the infrastructure. For instance, an asset may be weakened by constructive deficiencies associated with horizontal and vertical sealings that could subsequently result in excessive deformations/settlement differences.

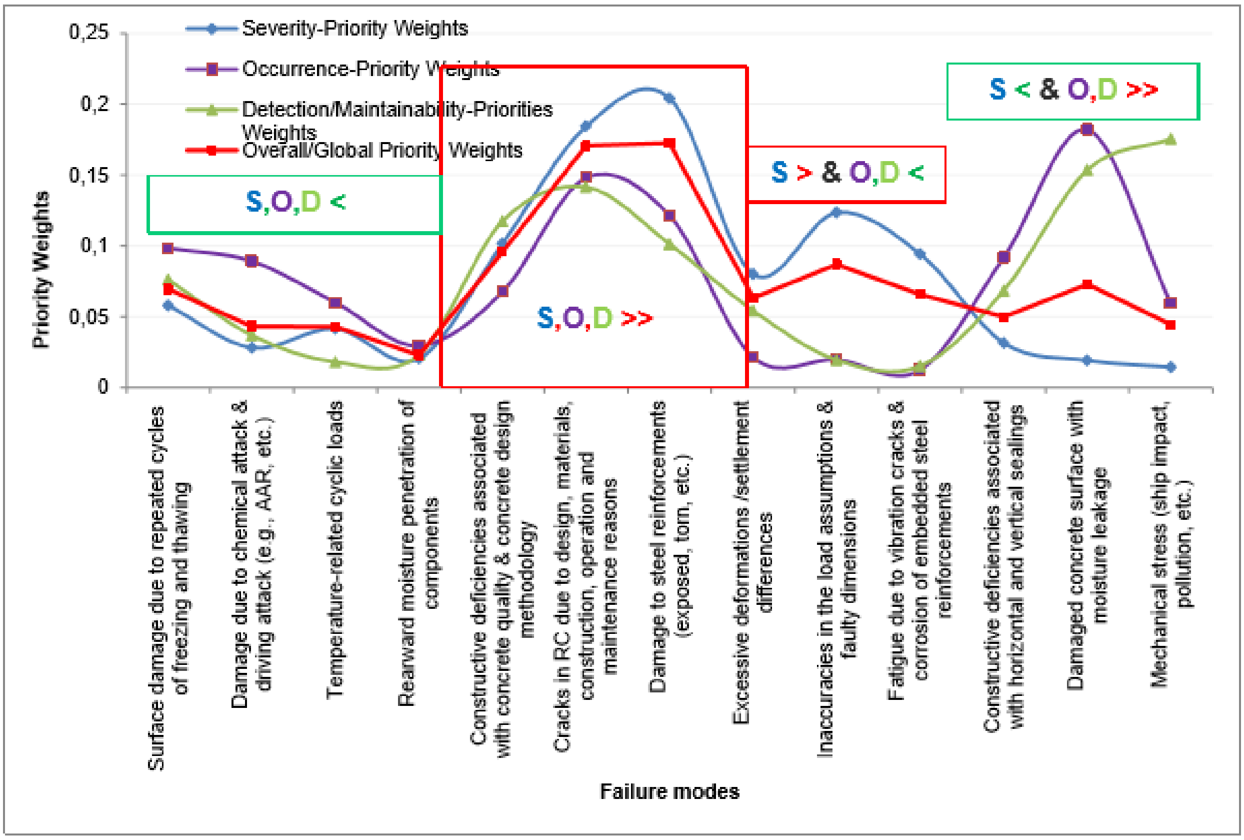

Figure 5: Computation of priority weights of various failure modes

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Some limitations of the proposed approach need to be emphasized. The approach largely depends on expert knowledge and damage data that entail a considerable amount of uncertainties. Moreover, the AHP methodology is considered costly, in terms of time given the number of cluster matrices required in the exercise. Nevertheless, the proposed approach attempts to address an important gap in practice by proposing a structured framework for ranking and selecting various failure modes for repair and maintenance. In addition, the selection models accounts for organizational capabilities, defined through the decision elements. The alternative risk assessment model, based on Analytical Hierarchy Process (AHP) serves as a tool to prioritize the Risk Priority Number (RPN) for each failure mode assessed and allow the identification of the most critical ones in the system. This aspect can ultimately be used as basis for strengthening the investment decision in favor of improving the reliability of the entire system. In general, our results indicate that the severity of potential consequences of a failure mode is the essential criterion in identifying the failure mode that posed the highest risk, and thus, that urgently need to be maintained.

To fully capture the linguistic vagueness behind the development of our comparison judgment matrices for the derivation of crisp priority weights, a fuzzy AHP may be used in future research studies. In addition, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) may be employed for evaluating and ranking various failure modes. Also, future works may focus on developing both qualitative and quantitative approaches, supported by Multi-Criteria Decision Making (MCDM) methods for the investigation of the emerging risk of infrastructure failure (Schmidt-Bäumler, 2017). A first step could consist of using the fuzzy logic approach, proposed by Bowles & Peláez (1995) in their study, to correct or mitigate the effects of a failure to be prioritized even though the available information might be vague, ambiguous, qualitative or imprecise. The Findings of such research projects could be used to strengthen the expressiveness as well as conclusiveness of the current condition grades and enhance decision making about prioritization of maintenance activities.

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