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Assessing the risk of disregarding urgent maintenance interventions on waterways infrastructures

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ABSTRACT: We propose a method for the prioritization of maintenance interventions already classified as urgent on waterways infrastructures, and especially locks. The method is based on the risk of the realization of a failure scenario due to damage processes. The probability of failure is computed by modelling the damage evolution as a stochastic process; the consequences which are considered are: additional cost of repairing after failure, number of fatalities, and the rate of lost customers upon an interruption of the lock service. Since quantifying all the consequences in economic terms could be difficult if not impossible, another approach is applied, which allows the aggregation of the consequences expressed in different scales. The suggested procedure, which has its roots in the probability applied to engineering, aims at supporting the planning of maintenance interventions on waterways infrastructures when resources and investment are limited.

1. INTRODUCTION

The geographical configuration of the German landscape presents an extended network of navigable rivers which is together with roads, rails and pipelines, part of the ground-based traffic route network of the Country.

In the 19th and 20th century the waterways network has been improved through the construction of locks, culverts, ports and weirs. Nowadays several of these infrastructures have almost reached their design working life and are affected by deterioration phenomena. Locks especially raise concerns because most of them have only one chamber and they are around 80-100 years old, showing evident signs of advanced degradation. Inspections have pointed out that maintenance is urgent; however because of economical and logistic reasons all the required repairing interventions cannot be immediately executed. For this reasons a method is required for ranking the damages according to their risk, and thus prioritize maintenance actions.

The method proposed in this paper is based on the probability and the consequences of failure due to damages. The consequences which are especially considered are the additional cost of repairing after failure, the human loss and the disruption in transportation. The probability of failure is computed by modelling the damage evolution through suitable stochastic processes. The disruption in transportation is expressed as the rate of ships which upon interruption abandon the network, and it can be computed applying queuing theory. Finally a Weighted Sum Method (WSM) is applied in order to evaluate the risk linked to each damage, and thus prioritizing maintenance. The paper is organized as follows: in Chapter 2 the current approach to waterways infrastructure management in Germany is reviewed, and its shortcomings are highlighted. In Chapter 3 the proposed method is introduced, and the most important steps are described in detail. In Chapter 4 a case study is developed in order to clarify the proposed approach. Finally in Chapter 5 the conclusion is drawn and a brief overview over the further steps of the research is given.

2. THE MAINTENANCE MANAGEMENT SYSTEM AND RELATED PROBLEMS

The current maintenance management system is based on the condition of the structure, which is inspected and repaired according to fixed cycles of 6 years. All objects are rated according to observed conditions, in increasing order of damage, from level 1 to level 4 (level 1 corresponds to absence of damage while level 4 indicates critical condition) and they are recorded in a standard format in a database software called WSVPruf, in which all the maintenance intervention can be traced back also.

Several objects have been classified as level 4, and therefore they should immediately undergo repairing and maintenance. However we are currently facing a backlog of maintenance intervention due to mainly 3 factors:

- Insufficient investment: in 2015 maintenance interventions for a total cost of circa 400 Mio € have been carried out; however in order to repair all insufficient conditions at least 1100 Mio €/year in addition are needed (BMVI 2015);
- Limited resources: the fixed cycles of 6 years represent an ideal clock for planning and executing inspection and repairs. However because of a lack of personnel and machines, not all the required intervention can be planned and executed in this time span;
- Availability issues: most of the intervention implies that the lock is put out of service for a certain period; if all the required interventions were simultaneously executed, huge portions of the waterways system would be interrupted.

The waterways where backlog of maintenance intervention at locks is most relevant are the Main, the Main-Donau-Kanal (MDK), the Neckar, the Wesel-Datteln-Kanal (WDK) and the Nord-Ostsee-Kanal (NOK).

In some cases, if the damage which cannot be immediately repaired evolves and a certain failure happens, the service of the lock has to be interrupted and an emergency maintenance intervention has to be carried out. We recall here that when waterways unexpected interruptions occur and last for long periods (in average more than two weeks), companies may confide in other means of transportation in order to receive provisions of raw materials and deliver products. Although after few weeks the functionality of the waterway is restored, goods that meanwhile have been diverted to railways or roads rarely return to waterways, resulting in a permanent loss of transported volume – and thus money - for the waterways network. Clearly, the willingness to wait of the ships or rather of the companies depends on the freight that is transported: from few days for fuels to a few weeks for buildings products.

The current approach to the prioritization of maintenance interventions is based on risk matrices, where the probability of failure and the consequences are assessed in a qualitative way, and the risk is obtained by multiplying them. The simplicity of this approach is unfortunately counterbalanced by its subjectivity and roughness. New strategies for the risk prioritization have been developed by the Federal Waterways Engineering and Research Institute (BAW), which can be classified into 3 main groups according to their focus:

1. Effect of the damage at structural level: this approach represents an attempt to apply the failure mode effect analysis (FMEA) to hydraulics infrastructures (Panenka & Nyobeu Fangue 2018);
2. Effect of repair intervention on transportation: this approach, which is based

on queuing theory, seeks to organize both planned and unplanned interruptions in such a way that the availability of the network is maximized (Marsili et al. 2018a);

3. Lifetime assessment: this approach, according to which the evolution of damages over time is modelled by stochastic processes and updated when the results of new inspection are available, in based on the assessment of the remaining life of the structure and the time-variant probability of failure (Marsili et al 2018b).

Each approach represents a partial contribution to solving the problem of the backlog of maintenance intervention. A combination of them would lead to a risk assessment in which both the probability of failure and all the possible consequences are quantitatively evaluated; however different scales and unit measures characterize the magnitude of the consequences. This problem should be solved in order to make the approach feasible.

3. PROPOSAL FOR A RISK-BASED PRIORITIZATION OF LOCKS MAINTENANCE INTERVENTION

This paper proposes an approach to short-time (within few years) maintenance planning. It proposes a method for ranking the risk linked with damages which are already classified as urgent. The method is based on the important assumption that failures due to damages happen independently from each other; the risk is evaluated considering the following criteria:

- The probability of failure linked to the damage process; this is the probability that an undesired event (a failure scenario) happens;
- The additional cost of repairing after failure;
- The fatalities at which failure could lead;
- The rate of goods which, in case of unexpected and long (more than 2 weeks) locks service interruption, are diverted to other transportation means and never returns to waterways; basically it corresponds to the rate of ships which abandon the system and never return.

In order to evaluate the contribution to the risk of each criterion, the Weighted Sum Method (WSM) is applied. According to this approach, all the criteria are expressed in the same scale and weighted with respect their importance.

The method has been summarized in Figure 1; in the following, the main steps of the procedure are briefly described.

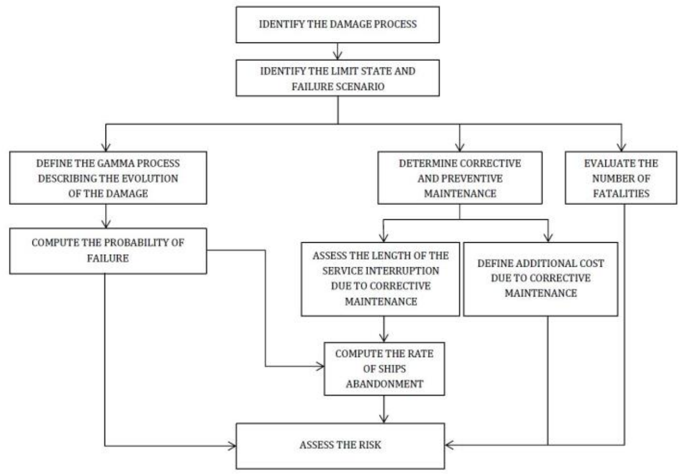

Figure 1 A diagram synthetizing the procedure for the risk assessment of neglecting maintenance interventions on locks.

3.1. Identify the failure scenario

The first step consists of taking stock of all the single damages recorded in WSVPruf and determine the damage processes affecting the structures. Here a certain engineering experience is required, since damage processes could depend on more than one factor, like material features and environmental conditions. Next, the short and long term consequences for each damage process will be established, which are respectively the not fulfillment of a given limit state and the realization of some failure scenario.

3.2. Compute the probability of failure

We assume that every damage process could be expressed through a certain parameter (i.e. the width of the crack, the percentage of damaged surface over the total surface etc. etc.), and the evolution of the parameter over time (which in fact is the evolution of the damage) can be described by a stochastic process (van Nortwjik 2009). The limit state $G(t)$ at time t has thus the following form:

$$G(t) = D_{lim} - D(t) \quad (1)$$

In which D_{lim} is the maximum damage accepted and $D(t)$ is the damage at time t. In order to identify the Gamma process describing the evolution of the damage, the Bayesian updating can be applied (Marsili et al. 2018b) considering data collected during inspections.

Finally the probability of failure related to degradation process will be computed:

$$p_f = p(G(t) < 0) = p(D_{lim} < D(t)). \quad (2)$$

3.3. Define the additional cost of corrective maintenance

Once the degradation process has been identified and the failure scenario has been determined, the repair intervention which should be carried out in case of failure is defined. Based on the repair intervention, additional costs due to the realization of the failure scenario will be estimated. These costs are given, for example, by an increased difficulty in performing the intervention, or by further consequences to which the realization of the failure scenario could lead. It is here also considered that, when a failure occurs, an emergency situation takes place, at which corresponds an increased burden of work, and to which some costs are associated.

3.4. Define the rate of ship abandonment

In order to compute the rate of ships which upon interruption abandon the network and never return we resort to queuing theory, and locks are model as queues with unreliable servers (Marsili et al. 2018a). Also here, we address the interested reader to previous works carried out by the authors, while in the following only a short overview on this approach will be given.

Yechiali (2007) has especially focused the attention on queues with servers subject to interruptions and customers having an impatient timer; modeling the problem as a two-dimensional continuous Markov process and computing the probability generating function, it is possible to compute explicitly parameters like the rate of customers immediately rejected, the sojourn time of customers which are served, and especially the rate of customers which are impatient and thus abandon the system. These parameters depend on several factors: the rate of breakdown, the mean time needed of repair, the customers' arrival rate and their impatient timer. The first two parameters can be evaluated according to the probability of failure and the length of the repairing intervention; the last two parameters, which essentially are the ships arrival rate at the lock and their willingness to wait when an interruption occurs, can be evaluated by exploiting the information about fleet structures, trajectories, freights volume and types collected in TRAVIS, a database created by the BAW in which relevant data about chunks of waterway in between two important inland harbors are given. Clearly, the more the freight is urgent, the more impatient a ship becomes, and it will abandon the system.

3.5. Application of the Weighted Sum Method for risk assessment and ranking

Finally the WSM (Yager 1988) is applied, and the risk linked to damages is ranked based on an aggregated weighted rating system. In this system each criterion *c* is expressed in terms of individual criterion ratings $R_{i,c}$ and the importance of the criteria is represented by weights w_c:

$$0 \leq w_c \leq 1\,. \quad (3)$$

To calculate the rating, two different equations can be used, which non-dimensionalize the criterion values; Eq. 4a is used in order to calculate the rating of risk for a criterion that should be maximized, while Eq. 4b is used for a criterion that should be minimized.

$$\begin{cases} R_{i,c} = \frac{x_{ic} - X_{c\,min}}{X_{c\,max} - X_{c\,min}} \; (a) \\ R_{i,c} = \frac{X_{c\,max} - x_{ic}}{X_{c\,max} - X_{cmin}} \; (b) \end{cases} \quad (4)$$

where $R_{i,c}$ is the rating of criterion c with respect the damage i, x_{ic} is the value for the criterion c, $X_{c\,min}$ is the minimum value for the criterion c, $X_{c\,max}$ is the maximum value for the criterion c. An aggregated weighted rating can be finally computed for the damage i:

$$R_{i,agg} = \sum_{c=1}^{n} R_{i,c} \times w_c \tag{5}$$

where n is the number of criteria. This expression can be interpreted as a weighted risk obtained by properly scaling each criterion in such a way that their values can be then easily aggregated.

4. CASE STUDY

The proposed approach is applied in order to prioritize maintenance interventions on the lock of the MDK. The situation at the MDK is especially critical, since all the 15 locks which mark the waterway have only one chamber: any interruption of the service of even one lock due to sudden failure will result in the traffic interruption at not only the MDK, but also in the entire waterway (Main and Donau). In order to repair the several damages at the locks of the MDK, inspection and maintenance are carried out on yearly basis instead of following 6-years cycles. However, because of the reasons listed in Chapter 2 and in particular because of the lack of resources, not all the damages classified as 4 can be effectively removed. For this reason a prioritization of maintenance intervention is highly recommended.

In Table 1 each damage has been listed and linked to the related limit state and failure scenario. In Table 2 parameters have been identified, which represent the evolution of the damage over time, and the limit value which corresponds to failure has been defined. Then a Gamma process which describes the evolution of damage along time has been determined, according to which the probability of exceeding the limit value can be computed. Then we also estimate the number of fatalities which could be provoked by the failure (Table 2), the additional costs of repairing the damage once that a failure event has happened and the rate of ship abandonment (Table 3). Although repairing before failure also implies to put the lock out of service for a certain period, the interruptions are planned and goods can be stored in advance; furthermore, the down time is limited. For this reason we assume that customers will abandon the system only in case of failure. As showed in Marsili et al. (2018a) the impatient timer T has been computed considering the freights which are usually transported through the MDK, and a mean value of t=10 days has been estimated. The probability to be up and down can be easily computed from the probability of failure and the length of the repairing intervention. Next, in Table 4, a normalized value for each criterion has been computed, and a weight has been given. We have considered here that fatalities are the worst consequences; thus, this criterion has obtained a higher weight. Finally the damages have been ranked according to the value of the aggregated risk.

5. CONCLUSION

This paper proposes an approach to the prioritization of maintenance intervention already classified as urgent. This approach has its roots in probabilistic performance evaluation applied to the engineering, and especially the model of damage processes as stochastic processes - according to which a probability of failure can be obtained - and queueing theory – according to which consequences such as the rate of ship abandonment in case of unplanned interruption can be easily computed.

The procedure, whose details have not been discussed here for the sake of brevity, could be a valuable tool in order to prioritize maintenance interventions classified as recommended in case of limited resources and investments. However several aspects should be further investigated, and especially the definition of the extent of damage to which corresponds failure, the accuracy of the gamma process describing the evolution of the damage, the assessment of the consequences of out of service, the assumptions underlying the model adopted to calculate the rate of lost customers. Our aim is to deepen the before mentioned research issues in the near future.

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Table 1 Locks affected by damages and related limit states and failure scenarios.

Lock	Year of construction	Damage process	Limit state	Failure Scenario
Leerstetten	*1980*	*Steel bars corrosion*	*Ultimate*	*Sudden collapse*
		Steel corrosion	*Serviceability/Ultimate*	*Deformation/collapse*
Kriegenbrunn	*1970*	*Cracks in reinforced concrete*	*Ultimate*	*Collapse*
		Steel bars corrosion	*Ultimate*	*Sudden collapse*
Hausen	*1968*	*Steel bars corrosion*	*Ultimate*	*Collapse*
Erlangen	*1970*	*Cracks in reinforced concrete*	*Serviceability/Durability*	*Filtering of water/damage accumulation*
		Steel corrosion	*Ultimate*	*Sudden collapse*
Eckersmühlen	*1985*	*Weathering of concrete surface*	*Serviceability/Durability*	*Damage accumulation*

Table 2 Damage processes and representing parameters; parameters of the gamma process describing the evolution of the damage over time, limit damage, corresponding probability of failure and number of fatalities.

Damage process	Parameter	Gamma process		d_{lim}	p_f	Fatalities
		α(scale)	β(shape)			
Steel bars corrosion - LEE	*Cross-section loss (%)*	*0,045*	*0,18*	*40%*	*0,035*	*2*
Steel corrosion - LEE	*Thickness reduction (%)*	*0,077*	*0,2*	*70%*	*0,035*	*0*
Cracks in reinforced concrete - KRI	*Crack width (mm)*	*0,2*	*0,2*	*2 mm*	*0,042*	*0*
Steel bars corrosion - KRI	*Cross-section loss (%)*	*0,022*	*0,18*	*40%*	*0,012*	*2*
Steel bars corrosion - HAU	*Cross-section loss (%)*	*0,022*	*0,18*	*40%*	*0,01*	*0*
Cracks in reinforced concrete - ERL	*Crack width (mm)*	*0,2*	*0,2*	*2 mm*	*0,033*	*0*
Steel corrosion - ERL	*Thickness reduction (%)*	*0,077*	*0,2*	*70%*	*0,052*	*1*
Weathering of concrete surface - ECK	*Thickness reduction (%)*	*0,054*	*0,22*	*70%*	*0,019*	*0*

Table 3 Length of the service interruption at locks, cost of preventive and corrective maintenance, rate of ship abandonment.

Damage process	Preventive maintenance		Corrective maintenance			ΔCost
	Interruption (days)	Cost (Euro)	Interruption (days)	Cost (Euro)	Rate of ship abandonment	
Steel bars corrosion - LEE	20	30000	180	100000	15,534	70000
Steel corrosion - LEE	30	12000	30	50000	7,299	38000
Cracks in reinforced concrete - KRI	30	45000	180	220000	15,897	175000
Steel bars corrosion - KRI	20	45000	180	220000	12,304	175000
Steel bars corrosion - HAU	40	45000	180	220000	11,571	175000
Cracks in reinforced concrete - ERL	10	8000	10	10000	2,357	2000
Steel corrosion - ERL	3	500	30	500	8,684	0
Weathering of concrete surface - ECK	40	45000	90	220000	10,790	175000

Table 4 Evaluation of normalized criterion and assessment of the risk of disregarding each maintenance intervention.

Damage process	pf			Fatalities			ΔCost			Rate of ship abandonment			Risk
	Value	R	W	Value	R	W	Value	R	W	Value	R	W	
Steel bars corrosion - KRI	0,012	0,048	0,1	2	1	0,4	175000	1,000	0,2	12,30	0,735	0,3	0,821
Steel bars corrosion - LEE	0,035	0,595		2	1		70000	0,400		15,53	0,973		0,775
Cracks in reinforced concrete - KRI	0,042	0,762		0	0		175000	1,000		15,90	1,000		0,501
Steel bars corrosion - HAU	0,01	0,000		0	0		175000	1,000		11,57	0,681		0,407
Weathering of concrete surface - ECK	0,019	0,214		0	0		175000	1,000		10,79	0,623		0,387
Steel corrosion - ERL	0,052	1,000		1	0,5		0	0,000		8,68	0,467		0,342
Steel corrosion - LEE	0,035	0,595		0	0		38000	0,217		7,30	0,365		0,157
Cracks in reinforced concrete - ERL	0,033	0,548		0	0		2000	0,011		2,36	0,000		0,007