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Risk based inspection planning for structural systems

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Abstract

Risk based inspection (RBI) planning for engineering systems is considered. Due to difficulties in formulating computationally tractable approaches for RBI for systems, most procedures hitherto have focused exclusively on individual components or have considered system effects in a very simplified manner only. Several studies have pointed to the importance of taking systems effect into account in inspection planning. Especially for large engineering systems it is not possible to identify cost optimal solutions if the various types of functional and statistical dependencies in the systems are not explicitly addressed. Based on new developments in RBI for individual components, the present paper presents an integral approach for the consideration of entire systems in inspection planning. The various aspects of dependencies in the systems are presented and discussed, followed by an introduction to the decision problems encountered in inspection and maintenance planning of structural systems. It is then shown how these decision problems can be consistently represented by decision theoretical models. The presentation of a practical procedure for the inspection planning for steel structures subject to fatigue concludes the paper.

Keywords: Inspection; Reliability; Updating; Deterioration; Structural systems; Decision analysis; Fatigue

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1. Introduction

Risk based inspection planning (RBI) for structures, as it is understood hereafter, is an application of the Bayesian decision analysis, aiming at the identification of the optimal inspection and maintenance strategies for deteriorating structures.[2] RBI procedures have their origins in the early 1970's, when quantitative inspection models for the first time were considered for the updating of probabilistic deterioration models by means of Bayes' rule, see [1]. In a fundamental study [2], a sophisticated procedure was presented that allows for the computation of the probability of fatigue failure for aircrafts under periodic inspections, taking into account the uncertainty in the inspection performance, which was later applied to optimise the inspection frequency, see [3]. This procedure, which takes basis in the Bayesian updating of the probability distributions describing the fatigue crack size, is computationally very efficient due to its closed form solution, but has the disadvantage of not being flexible in regard to changes of the stochastic deterioration and inspection models. This limitation was finally overcome in the mid 1980's with the development of structural reliability analysis (SRA), enabling the updating of the probability of events, see, e.g. [4] and [5]. Based on SRA, RBI procedures were developed mainly for offshore structures subject to fatigue, e.g. [6–10]. In the early 1990's, first applications of RBI were reported, see [11–15]. Additional efforts have been directed towards the application to structures other than fixed offshore steel structures subject to fatigue, see [16] for references, and towards the verification of the probabilistic models through the analysis of in-service experiences, see, e.g. [17] and [18]. Because of the large efforts required for the probability calculations (both by means of SRA or simulation), the application of the methodology has been limited to relatively few industrial projects in the past. This drawback has been overcome recently by the generic approaches to RBI, as proposed in [19] and elaborated in [16] for steel structures. These developments greatly increase the computational efficiency in a consistent manner, as will be outlined later. In doing so, they facilitate the integral consideration of systems and thus form the basis for the RBI of structural systems presented in the following.

Traditionally, RBI has focused on individual structural details because of the computational limitations as discussed above. However, the effect of stochastic dependencies in the deterioration model from one hot spot to another has been investigated in some studies, including [20–23], but these studies only partly include these effects in the decision modelling. Although its importance is pointed out by many authors, a procedure aiming at the integral consideration of the entire system in RBI is attempted in only few studies, e.g. [24]. These approaches are based on an informal decision analysis where the number of considered hot spots is systematically reduced. Unfortunately, as noted in [22], they have not been demonstrated to be practical, mainly due to numerical effort and stability. As demonstrated in this paper, the generic approach to RBI provides the means to overcome these difficulties.

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[2] In the process industry, RBI is typically based on frequency data and accounts for inspection quality in a qualitative manner, see, e.g. [43]. Such semi-quantitative approaches are generally not appropriate for deteriorating structures, as discussed in [16].

2. Identifying and defining the system

Structural systems are generally subject to deterioration at various locations, depending on the loading, the environment and the structure itself. The identification of these potential failure modes and locations is an essential part of the asset integrity management strategy and should be performed by means of semi-quantitative risk analysis procedures prior to the fully quantitative RBI analysis, see, e.g. [25]. Especially the problem of so-called gross errors must be covered by such procedures.

Analogous to the notation used in fatigue analysis, the term *hot spots* is in the following applied to denote the identified potential locations of deterioration in a structure. Therefore, the structural system is for the purpose of RBI represented in terms of its hot spots and their interrelations (which can be of a functional or statistical nature); the latter are discussed in the subsequent section. This notation also applies to other deterioration mechanisms such as corrosion. When non-localised deterioration is considered, this requires the discretisation of the structure in elements whose size depends on the correlation length of the deterioration process.

3. System effects in RBI

The structural system is defined by the individual hot spots and their interrelations (the statistical and functional inter-dependencies). In past applications of RBI, as discussed in Section 1, the considerations were limited to the individual hot spots, which are related to the system by means of the cost model; the cost of failure of the hot spot is commonly expressed as a function of the importance of the hot spot for the system. Other system effects were not considered. In the following, first the different types of interrelations are introduced; these definitions facilitate an overview on the system effects in RBI. Thereafter, it is considered how to infer the condition of a hot spot from inspection results obtained at other hot spots. This aspect is of special importance for RBI of structural systems.

3.1. Dependencies in deterioration performances between hot spots

The deterioration performances of the individual hot spots in a system are generally interdependent. If the deterioration at hot spot i at time t is described by the marginal probability density function of the size of the largest defect, S_i, then the dependency between the deterioration at the n hot spots in the system can be expressed by the joint probability density of all S_i. Such a model is illustrated by Fig. 1, where it is assumed that the dependency is described with sufficient accuracy by the covariance matrix $V_{\underline{\underline{SS}}}$.

The stochastic dependency is caused by common influencing factors within the system. For fatigue, entire groups of hot spots are generally subject to the same realisation of the load process. The fatigue loading at these hot spots is, therefore, highly dependent given that no observations of this process are available.[3] Additionally, the weld quality may be similar within one production series,

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[3] When observations are available, then the common influencing variable often becomes deterministic or its uncertainty is reduced to the extent where it is only of minor importance. This variable can, thus, be explicitly addressed and then only represents a functional dependency but no statistical dependency.

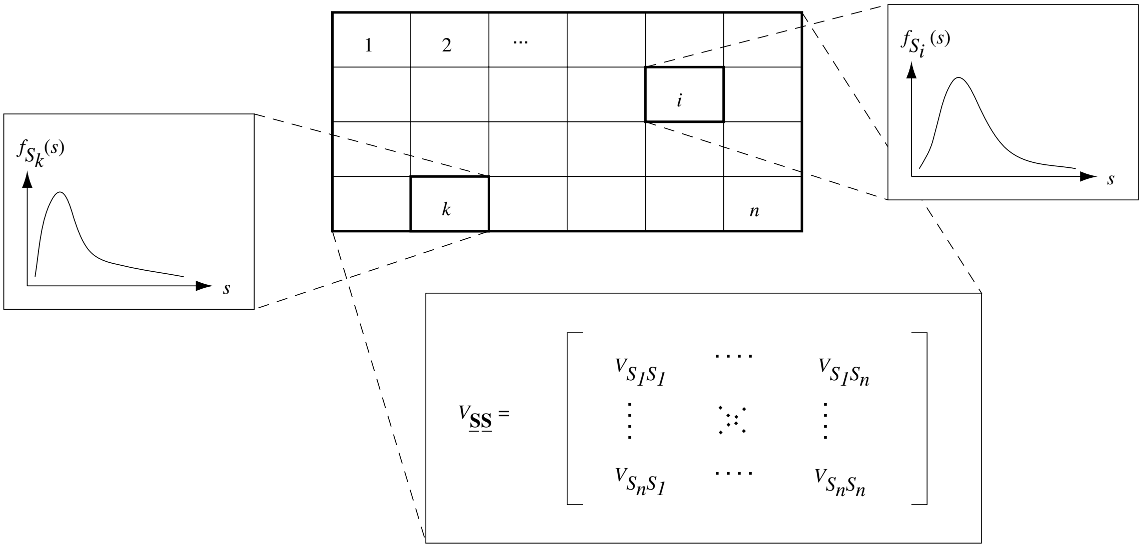

Fig. 1. Illustration of a system model for deterioration at time t.

introducing a dependency between the individual initial defect sizes and between the individual SN fatigue resistances. For corrosion subjected steel structures, the environmental conditions, like temperature and pressure, are often highly dependent between different hot spots in the system.

For steel structures, only few published studies are concerned with the modelling of such dependencies. In [27], the dependency in the weld quality from one hot spot to the next is assessed by comparing the scatter in fatigue performance within one production series to the scatter in a general group of hot spots represented by the same SN curve. In [28], the stochastic dependency between the fatigue performances in individual segments in a mooring chain is estimated based on engineering judgement. For corrosion of steel structures, the authors are not aware of any publications dealing with large-scale spatial dependencies of the corrosion process (i.e., dependencies between individual hot spots and not within one hot spot). For most applications, it is therefore required to estimate the degree of dependency between the influencing factors at the different hot spots. Based on these estimates, the dependency between the deterioration performances at the hot spots is calculated.

3.1.1. Describing the stochastic dependency through common influencing variables

It is advocated that, if possible, the dependency is not expressed by correlation coefficients between the random variables describing the behaviour of the individual hot spots, as depicted in Fig. 1, but by explicitly modelling the common influencing variables. As an example, consider the stochastic dependency between two hot spots in an offshore structure subject to fatigue: It is commonly assumed, see [29], that the uncertainty in the fatigue stress ranges at the hot spots, B, can be expressed as the multiplication of the uncertainties from the individual contributions B_i

$$B = \prod_i B_i. \tag{1}$$

The realisation of the sea state is by nature the same for the two hot spots; the random variable B_S describing the uncertainty in the sea state prediction is thus the same for the two hot spots. On the other hand, if the two hot spots are of a different geometry, it can be assumed that the random variables describing the model uncertainty on the stress concentration factor, B_H, have independent realisations at the two hot spots. Such reasoning can be made for all B_i and it is possible to calculate a corresponding correlation coefficient ρ between the random variable B at the two hot spots. However, ρ cannot represent the full information contained in the above description; therefore, it is mathematically beneficial to directly model the individual common influencing variables such as B_S. Additionally such an approach is more transparent as it documents the underlying assumptions.

3.2. Dependency of failure consequences on the state of the system

In previously published RBI procedures, it is assumed that the consequence of hot spot failure can be modelled by a fixed cost C_F. This cost accounts for the conditional probability of collapse of the structure given hot spot failure, $P(COL|F)$, as well as any other follow-up consequence. For offshore structures, it has been demonstrated, e.g. [30] and [31], how this conditional probability can be calculated as a function of a deterministic indicator named residual influence factor (RIF) or alternatively damaged strength ratio (DSR). This indicator is defined as the ratio of the overall capacity of the structure modelled with failure assumed in the considered hot spot and the capacity of the intact structure.

As discussed in [26], such an approach neglects that the consequence of a fatigue failure depends also on the state of the other hot spots. In other words, the probability of structural collapse given failure of i hot spots does generally not increase linearly with i; not to account for this relationship explicitly is often non-conservative. Ship structures for example are generally highly redundant. Failure of one hot spot normally has only a small influence on the overall structural capacity; the calculated RIF is thus very close to one. Following the classical approach, this implies that such a failure has no bearing on the probability of structural collapse. However, the simultaneous occurrence of several hot spot failures, respectively, the growth of a crack through several hot spots, has been observed to lead to collapse of entire ship structures.

It has been found that in general these effects cannot be considered explicitly [26], because accounting for all possible combinations of hot spot failures is not computationally tractable. Instead it is suggested, following an argument in [26], that crude inspections, which allow for the identification (and subsequent repair) of failed hot spots, are performed in regular intervals for all hot spots. These intervals should be identified by consideration of the dependencies between the hot spots in such a way that the probability of two hot spot failures coinciding becomes acceptably small.

3.3. Dependency of inspection costs on the number of inspected hot spots

The marginal cost of inspection of the ith hot spot is generally not independent on the total number of inspected hot spots. For many structures, the inspection costs consist to a large extent of fixed components, such as the cost of accessing the hot spots or the cost of temporary unavailability of the structure, and only a minor part of the costs is variable. The cost of inspection of the individual hot spot, C_{Insp}, must thus be evaluated by considering the total number of inspections, which will favour the grouping of inspections into inspection campaigns. To account for this effect in the inspection optimisation is straightforward, once the relation between the number of inspected hot spots and the inspection costs is identified, see [32].

3.4. Dependency between the inspection performance at different hot spots

The inspection performance is generally not independent from one hot spot to the next, due to common influencing factors, such as the inspector characteristics or environmental conditions. A model for these dependencies is proposed in [33]. There it is concluded that the influence of inspection dependency on the updated system reliability in general is not crucial for structures subject to flaws and fatigue cracks; the inclusion of the inter-dependencies in the modelling of the inspection performance is, therefore, advocated only for very critical structural systems or in systems with a very large number of similar hot spots.

3.5. Inference from inspection results at other hot spots

An important effect of the dependencies between the deterioration behaviour at different hot spots is that the outcome of an inspection at one hot spot contains information about the state of the other hot spots. For systems with a large number of hot spots, this is of utmost importance, because it allows basing the maintenance decisions on a set of "sample inspections". Considering offshore structures, it is noted in [34] that full inspection coverage of the deterioration sensitive parts is not a realistic assumption. The same holds for most large engineering structures, especially for those where in principle all spots are "hot", such as pipelines or most large concrete structures. In practice, for such structures NDE (non-destructive evaluation) is applied to only a few hot spots because full inspection coverage would not be feasible.

To assess the optimal inspection coverage, it is required that the dependency between the deterioration at different hot spots is addressed by the inspection planning procedure. This paper introduces such a procedure, based on previous developments by the authors published in [32,35].

4. Risk based inspection planning for single hot spots

This section provides a very brief introduction to RBI for single hot spots; a comprehensive introduction is available in [16]. This is followed by an equally short description of the generic approach to RBI [16,19], which has been developed to increase the computational efficiency of RBI. An efficient RBI procedure for single hot spots forms the basis of the system RBI presented thereafter.

RBI is an application of the pre-posterior analysis of the Bayesian decision theory as described in [36]. Pre-posterior analysis facilitates the calculation of the value of information (of the inspection) by modelling all relevant events and decisions and by evaluating the expected utility with respect to all random parameters (using a generic notation these are the state of nature θ and the inspection outcomes $\underline{\mathbf{z}} = (z_1, \ldots, z_{n_{\mathrm{insp}}})^{\mathrm{T}}$).

4.1. Determination and optimisation of inspection strategies

When a specific deterioration phenomenon is considered, an inspection strategy for an individual hot spot defines when to inspect using which inspection technique. This is summarised in a vector $\underline{\mathbf{e}} = (e_1, t_1, \ldots, e_{n_{\mathrm{Insp}}}, t_{n_{\mathrm{Insp}}})^{\mathrm{T}}$, where e_i describes the inspection type applied at time t_i. In addition to $\underline{\mathbf{e}}$, a maintenance strategy must also include a repair strategy d, which describes the repair action a to perform as a function of the inspection outcome z. Assuming a time-independent repair strategy, it is therefore

$$a = d(e, z). \tag{2}$$

A typical repair strategy is to repair all identified defects or to repair all identified and measured defects larger than a certain size.

The pre-posterior decision problem is typically modelled by means of decision trees. Full decision trees include all possible combinations of $\underline{\mathbf{e}}$, $\underline{\mathbf{z}}$, d and θ, which makes the decision trees intractably large. For this reason, some simplifications are introduced, such as the assumption that any repaired hot spot is brought back to its original undamaged state but performs statistically independent of this [16,19]. When applying these assumptions, the decision tree is fully described by the failure rate conditional on no repair after all previous inspections, together with the probability of a repair at the various inspection times t_i. These probabilities and failure rates are calculated from the (mostly empirical or semi-empirical) probabilistic deterioration and inspection models, using SRA or simulation techniques.

When a corresponding cost is assigned to the different events (failure F, repair R and inspection I) and a representative real interest rate r is identified, the expected cost $\mathrm{E}[C_{\mathrm{T}}]$ of an inspection strategy ($\underline{\mathbf{e}}$, d) can be calculated following the rules of decision theory. Given that the probabilities

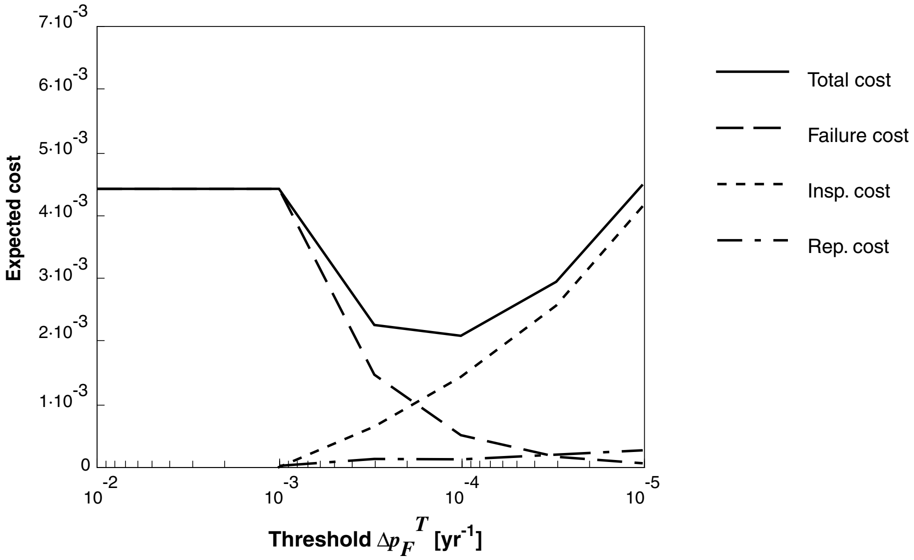

Fig. 2. Expected costs (net present values) for different thresholds on the annual failure rate; from Straub [16].

are evaluated prior, explicit solutions are available for the calculation of the total expected cost [16].

Because the number of potential inspection strategies is very large, the general optimisation problem is replaced by a restricted optimisation where the inspection times are determined as a function of a threshold on the failure rate, Δp_F^T. This is known as the *threshold approach* [19], which has the advantage that the optimisation parameter Δp_F^T is also the relevant criteria for demonstrating compliance with the acceptance criteria Δp_F^{max}. Assuming that the same NDE technique e is applied at all inspections, the optimisation problem is written as

$$\min_{e,\Delta p_F^T,d} \mathrm{E}[C_T(e, \Delta p_F^T, d, T_{SL})] \quad \text{s.t.} \quad \Delta p_F^T \leqslant \Delta p_F^{max}, \tag{3}$$

where T_{SL} denotes the service life time of the structure. Fig. 2 shows an example of an optimisation with fixed inspection technique e and fixed repair strategy d.

5. Generic approach to RBI

The probability calculations are computationally very demanding, especially for fatigue problems. This has hindered the application of the RBI methodology in practice and has been prohibitive for the consideration of the system effects. The generic approach to RBI [16,19] was developed to overcome these limitations. The core of the generic approach to RBI is the pre-fabrication of inspection plans for generic hot spots which are representative for the particular hot spots in the considered structures. These pre-fabricated plans are termed *generic inspection plans*. The inspection plans for the individual hot spots in a structure are then obtained from the generic inspection plans through an interpolation procedure. All hot spots that are represented by the model are fully described by the so-called generic parameters. These are the input parameters to the model that vary from hot spot to hot spot and which are indicators of the relevant deterioration mechanism. For structures subjected to fatigue, typical examples of such generic parameters are, e.g., the calculated design fatigue life T_{FL} (respectively, the dimensionless fatigue design factor *FDF*[4]), other loading characteristics, the applied SN curve (which is representative for the detail type and the environment) and geometrical parameters such as the wall thickness at the hot spot. Because these parameters are obtained from standard fatigue evaluation procedures, the RBI can, in principle, be performed without specialist knowledge once the generic inspection plans are available.

The computational efficiency of the generic approach is founded in the replacement of the demanding probability evaluations by an interpolation of the probabilities, which are calculated previously and stored in the generic database. Although the calculations of the generic inspection plans are still demanding, these are performed at a previous stage; the extraction of inspection plans for particular structures from the generic database on the other hand is very efficient and can be integrated in the daily asset integrity management procedures of the owner or operator of the structure. When simulation is applied, the generic approach reduces the CPU time required

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[4] The *FDF* is a deterministic safety factor, defined as the ratio of the calculated design fatigue life to the design service life.

for the calculation of the inspection plans by a factor which is in the order of 10^4 (from hours and days to few seconds). Details on the computational aspects are provided in [37].

As an example of the generic approach consider Fig. 3. The required inspections to comply with given acceptance criteria can be evaluated as a function of the *FDF*. For fixed values of all other parameters, the inspection times are obtained as a function of the *FDF*. Similarly, the expected costs can be expressed as a function of the *FDF* (Fig. 4).

6. RBI for systems

In the following, the general decision-theoretic problems for inspection planning of structural systems are introduced. Two fundamentally different types of structural systems with respect to

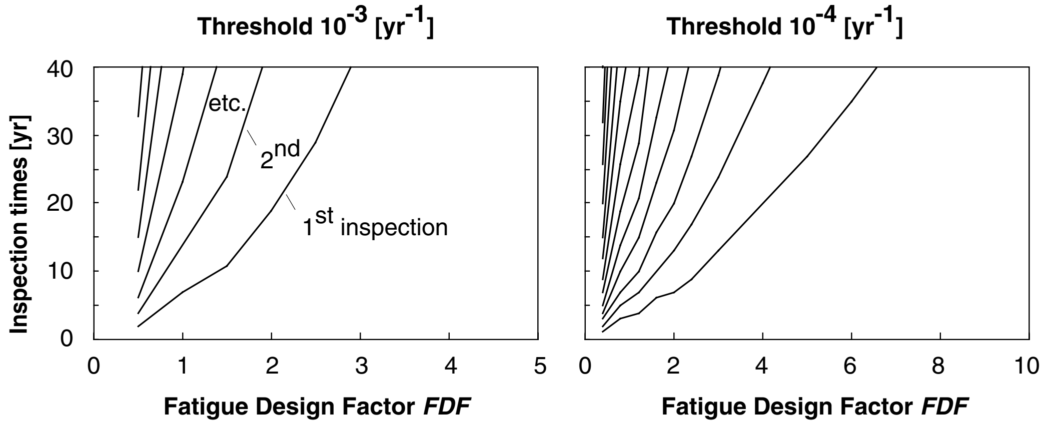

Fig. 3. Inspection times as a function of the *FDF* for two different thresholds on the annual probability of failure; from Straub [16].

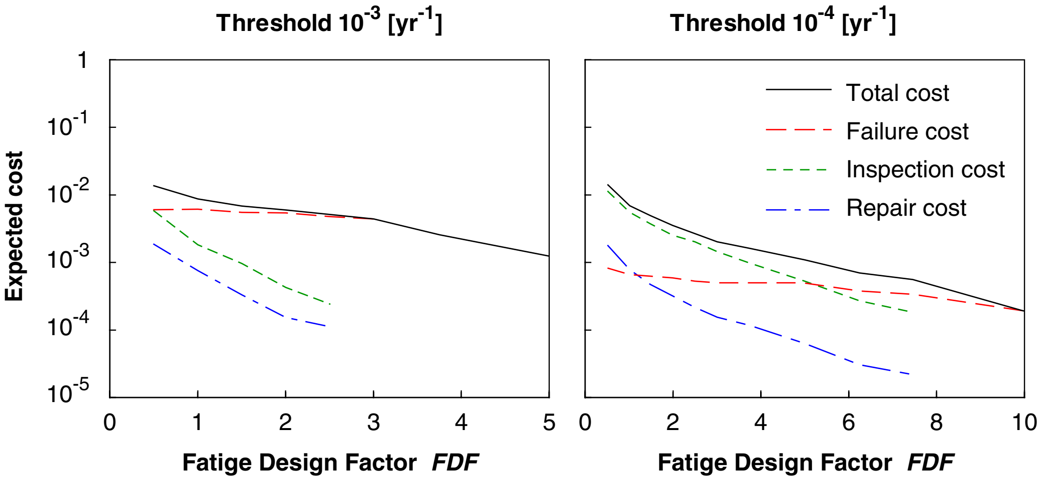

Fig. 4. Expected costs as a function of the *FDF* for two different thresholds on the annual probability of failure; from Straub [16].

the underlying decision model are identified: The first type are structural systems where mitigation actions, such as repair or replacement, are performed only for the entire system, the second type are those where the mitigation actions are carried out only for a selection of hot spots, based on knowledge of the condition of the individual hot spots. These two situations are considered separately in the following.

6.1. Common mitigation actions

In structural systems consisting of hot spots subject to identical conditions and for which preventive and corrective maintenance actions are the same for all hot spots, the decision on repairing all hot spots is taken when a certain percentage of the hot spots have reached an unacceptable state. As an example, concrete structures subject to corrosion of the reinforcement often fall into this category. For such systems, the inspection and maintenance planning problem is equivalent to a quality control problem. For time invariant problems, the optimisation of the inspect effort is straightforward and can be performed according to the classical references, e.g. [38]. The relevant question is how many hot spots to inspect (the optimal inspection coverage) using which technique. In [39], this approach is applied in a highly simplified manner to the determination of the cost optimal inspection coverage for pipes.

Considering deteriorating systems, in [40] the classical solution is extended and so-called condition indicators are introduced. The indicators (inspection results) give information about the condition of the overall structure at different points in time. By evaluating this information at different times and for different inspection coverage, the optimal number and time of inspections can be assessed. This problem can be represented by a decision tree similar to that used for single hot spots. The two mitigation actions considered in this tree are then "no action" and "repair of all hot spots in the system". The related optimisation is more demanding because the number of hot spots to inspect is an additional parameter which must be considered together with the inspection times. The solution of such problems requires that the general optimisation problem is constrained, in analogy to the threshold approach for single hot spots, in order to be computationally feasible. A possible solution is to fix the percentage of hot spots which are inspected and then to determine the inspection times using the threshold approach. By doing this for different percentages of hot spots inspected, the optimal inspection coverage can be identified. To enhance the efficiency, it should be envisaged to solve the problem through a generic approach.

RBI for systems with common mitigation actions is not considered further in this paper. Instead focus is directed on structures which have large reliabilities against deterioration failures and for which the replacement of entire systems or sub-systems is not economical. For these structures, mitigation actions are generally planned and performed for individual hot spots. Typical examples are steel structures subject to fatigue.

6.2. Individual mitigation actions: adaptive strategies

In many structural systems, hot spots are only repaired after a previous indication of a defect, i.e., decisions on repair actions are not made for a group but only for individual hot spots. The inspection outcome of a hot spot has thus no direct bearing on the repair decisions for other hot spots. For illustrational purposes, consider a simple system with two dependent hot spots A and

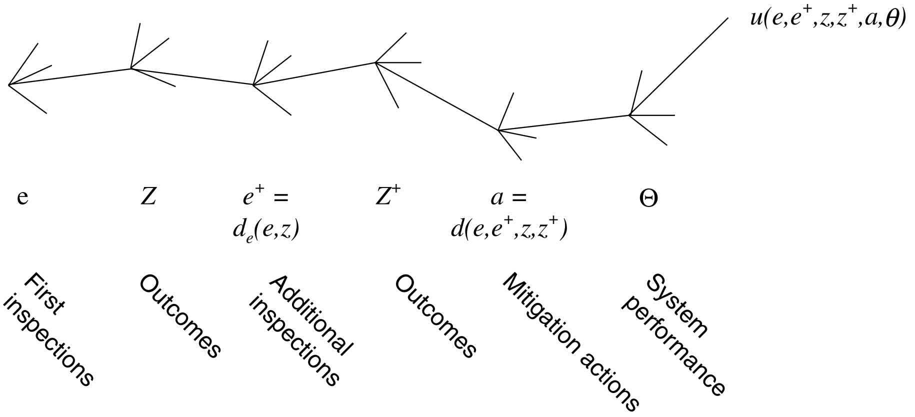

Fig. 5. Decision tree illustrating the adaptive strategy to inspection planning for systems.

B, where A is inspected. Even when a large defect is indicated at A, B will not be repaired unless a defect is indicated at B itself. A reasonable strategy is thus to inspect A and to decide on an inspection of B based on the outcome of the first inspection. In Straub and Faber [35] such approaches to inspection planning are denoted adaptive strategies, because the inspection plan for a specific hot spot is adapted to the inspection outcomes at other locations. As demonstrated in [35], system effects can only be accounted for by applying such adaptive inspection planning procedures.

Fig. 5 shows a simple adaptive decision model, where the classical decision tree from Bayesian pre-posterior decision analysis is extended by including a second decision rule d_e. This decision rule determines the additional inspections e^+ to be performed, based on the outcome of the first inspections, z. The repair decision is given by the decision rule d, based on the outcome of all inspections.

The decision tree in Fig. 5 includes only one additional decision parameter, namely $d_e(e,z)$. However, the determination of optimal adaptive inspection plans is far more complex than the RBI for individual hot spots. This has several causes which are listed in the following:

- The number of possible outcomes of z is much larger than for single hot spots. For the latter, it is sufficient to consider only no-indication or indication (with an additional measurement) of the defect. For the system, the number of indications can vary between zero and n_{Insp}, the number of inspected hot spots.
- The assumption of no-indication at the inspections is not justified. Unless the number of inspected hot spots, n_{Insp}, is very small, the probability of no-indication at all inspected hot spots is low.[5]

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[5] Most publications that consider inspections on systems make the assumption of no-indication. If no-indication is assumed, the solution of the optimisation problem is greatly facilitated, because simplifications can be made similar to those for RBI for single hot spots.

- The decision rule d_e is not obvious: In contrast to the decision rule on the repair action, where only the state of the individual hot spot is of concern, d_e is a function of the inspection outcome z, which includes a large number of different possible values, as discussed above. In addition, whereas d is either no-action, repair or replacement, d_e can result in different numbers of additional inspections.
- The decision tree as depicted in Fig. 5 is not the only potential strategy. In principle, it is also possible that after the performance of a second set of inspections e^+ with respective outcomes z^+ it is decided to perform additional inspections.

The complexity of the problem, as outlined in the above list, makes it computationally untractable to perform a direct optimisation of the inspection efforts in such systems, because of the resulting enormous number of different possible combinations of events and decisions. Restricting the number of such combinations (corresponding to the branches in the decision tree) to the degree where the problem is mathematically tractable has not proved successful so far. In contrast to the decision models for individual hot spots and for systems with common mitigation actions, for systems with individual mitigation actions all simplification rules considered in the past lead to solutions which are in many cases far from the optimal one.

In the following section, the full optimisation problem is approached from the optimisation of the inspection efforts for the individual hot spots, using the *value of information* concept from the Bayesian decision theory.

7. RBI for systems using the value of information concept

This section summarises the methodology introduced in [32], developed for structural systems subject to deterioration for which the decisions on mitigation actions are taken for all hot spots individually, following the above discussion. The methodology is based fully on the generic approach to RBI: its basic idea is to replace the optimisation of the inspection efforts for the entire system by the optimisation of the inspection efforts for all hot spots individually, which is facilitated by the generic approach to RBI. The system is introduced in the analysis by considering the effect of the different dependencies on the parameters of the hot spots. If the parameters of the individual hot spots are constantly updated with all available information in the system, then it is ensured that the optimal inspection plan for the individual hot spot is also optimal in view of the entire system.

The updating of the hot spot parameters through information from other hot spots is performed in a simplified manner, based on the *FDF*:[6] When inspection outcomes from dependent hot spots are available, this information is used to update the reliability of the considered hot spot.[7] For computational efficiency, the updated reliability is then assumed fully represented by

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[6] Note that the concept is developed for fatigue subjected hot spots. The extension to other deterioration modes is in principle straightforward, but requires that an indicator corresponding to the *FDF* is formulated. Such an indicator is utilised in [44] for corrosion.

[7] This strategy is implicitly adaptive: the inspection efforts at the non-inspected hot spots are determined as a function of the *FDF*. By updating the *FDF* based on the inspection outcomes at the other hot spots, the inspection efforts at the non-inspected hot spots are automatically adapted.

an updated value of the *FDF*, whereas all other parameters do not change. This is illustrated in Fig. 6 which shows the updated reliability of a hot spot after the inspection of dependent hot spots, together with the corresponding updated *FDF* (where the updated *FDF*s are indicated by FDF''). The details and the implications of this procedure are documented in [32].

It is noted that the effect of dependency, as illustrated in Fig. 6, depends on the applied probabilistic model and especially on the assumed dependency between the hot spots. The results presented in this paper are based on the (simplified) assumption of a full correlation between the stress ranges at the hot spots and independency between all other random variables.

The above described procedure is a very efficient tool for the inspection planning of systems, because for each value of the *FDF* the corresponding optimal inspection plan is readily obtained using the generic approach. It facilitates the management of all available information of the system and the calculation of the actual reliability of all hot spots and thus the entire system at any time. The optimisation of the inspection efforts, however, requires that all (functional and statistical) dependencies between the hot spots are explicitly addressed and quantified. After an inspection is performed such a task is straightforward according to the methodology outlined in the above, but in inspection planning (pre-posterior analysis), it is required that the effect of a planned inspection on the dependent hot spots is quantified also. A direct effect of such a planned inspection is that the marginal cost of inspection for the other hot spots is decreased, which is easily included in the analysis. More difficult to include is the aspect that each planned inspection will potentially supply information about the condition of all dependent hot spots; this is addressed in the following, using the value of information concept from the Bayesian decision theory as described in [36].

An inspection at hot spot A has a value because it facilitates the targeted application of mitigation actions on A. When performing RBI for single hot spots, this value is balanced with the cost of the inspections in order to identify the optimal inspection efforts. For the system, an

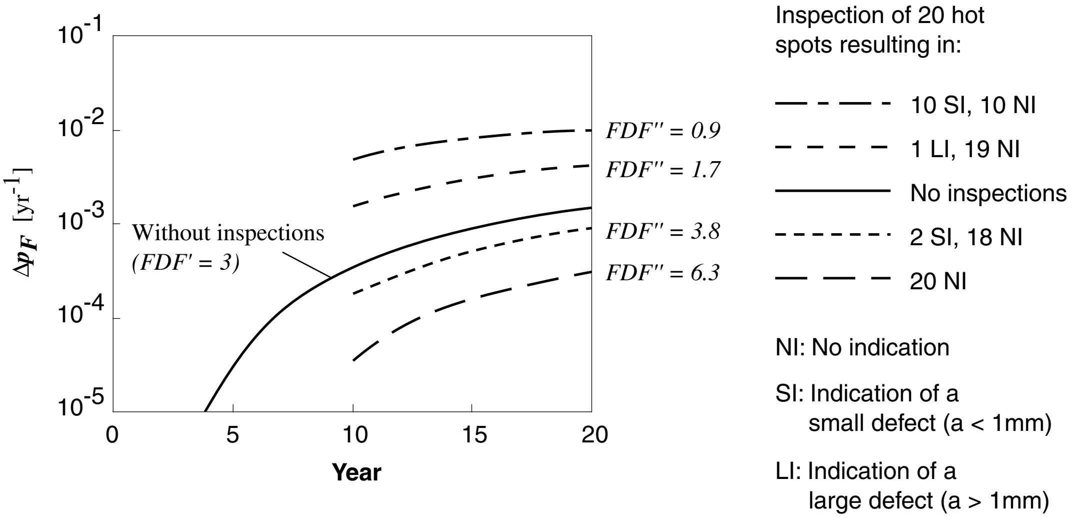

Fig. 6. The updated reliability by considering inspections of dependent hot spots in the system, from Straub and Faber [32].

inspection of hot spot A has an additional value, because it also provides information about the hot spot B (if B is dependent on A). Inspecting A has a value for hot spot B because the additional information enhances the chance that the planned inspection efforts on B are optimal.

7.1. Calculating the expected value of information from an inspection with respect to the entire system

As noted above, for a given structure (with a particular service life) the *FDF* is the main indicator for the reliability of the individual hot spot. For each given *FDF*, a corresponding optimal inspection strategy can be found in accordance with Fig. 2 for this individual hot spot; therefore, it is possible to calculate the minimum expected cost for a given hot spot as a function of the *FDF* and to identify the optimal inspection strategy as a function of the *FDF*. It can be observed that the optimal number of inspections in general decreases with increasing reliability.

An inspection strategy is in the following referred to as $\underline{\mathbf{S}} = (\underline{\mathbf{e}}^{\mathrm{T}}, d)^{\mathrm{T}}$ and the total expected cost is given as a function of the strategy and the *FDF* as $\mathrm{E}[C_{\mathrm{T}}(\underline{\mathbf{S}}, FDF)]$; this is readily evaluated using the generic approach. Based on a fatigue analysis, the hot spot B is described by FDF'_{B} and the corresponding optimal inspection strategy for this hot spot is $\underline{\mathbf{S}'_{\mathrm{B}}}$. When hot spot A is inspected with inspection outcome z_{A}, the *FDF* of B is changed to $FDF''_{\mathrm{B}}(z_{\mathrm{A}})$ according to the above procedure, and the optimal inspection strategy is now $\underline{\mathbf{S}''_{\mathrm{B}}}$. If $\underline{\mathbf{S}''_{\mathrm{B}}} \neq \underline{\mathbf{S}''_{\mathrm{B}}}$, then the original strategy is no longer optimal. The new strategy which is now followed results in expected savings given by Eq. (4)

$$\mathrm{CVSI}(z_{\mathrm{A}}) = \mathrm{E}[C_{\mathrm{T}}(\underline{\mathbf{S}'_{\mathrm{B}}}, FDF''_{\mathrm{B}}(z_{\mathrm{A}}))] - \mathrm{E}[C_{\mathrm{T}}(\underline{\mathbf{S}''_{\mathrm{B}}}, FDF''_{\mathrm{B}}(z_{\mathrm{A}}))], \tag{4}$$

CVSI abbreviates *conditional value of sample information*. CVSI is the value that the inspection results in A have by supporting the decisions on the actions in B. Because $\underline{\mathbf{S}''_{\mathrm{B}}}$ is the optimal strategy given the posterior FDF'', Eq. (4) will always result in a value equal to or larger than zero. The term *conditional* indicates that the CVSI is representative for a particular inspection outcome z_{A} in A. Before the inspection, i.e., in the inspection planning phase, the realisation of the outcome z_{A} is unknown, but can be modelled by the distribution of Z_{A}[8] as a function of the prior model for A and the inspection model; furthermore, $f_{Z_{\mathrm{A}}}(z_{\mathrm{A}})$ forms part of the generic inspection plans and is thus readily available. The expected value of an inspection in A with respect to B is obtained as

$$\mathrm{EVSI} = \int_{Z_{\mathrm{A}}} f_{Z_{\mathrm{A}}}(z_{\mathrm{A}}) \mathrm{CVSI}(z_{\mathrm{A}})\, \mathrm{d}z_{\mathrm{A}}. \tag{5}$$

Fig. 7 shows the EVSI (expected value of sample information) for one example case as a function of the initial *FDF* in A and the inspection year. It is observed that more information can be obtained from inspecting a hot spot with a lower *FDF*, respectively, lower fatigue reliability, especially when inspecting at earlier points in time. The value of the obtained information decreases with time, because the remaining service life determines the maximum possible benefit of an inspection, yet for higher values of the *FDF* this is compensated by the fact that more information is obtained at later stages.

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[8] For fatigue problems, it has been experienced that it is generally sufficient to distinguish only between two states of Z, such as indication and no-indication.

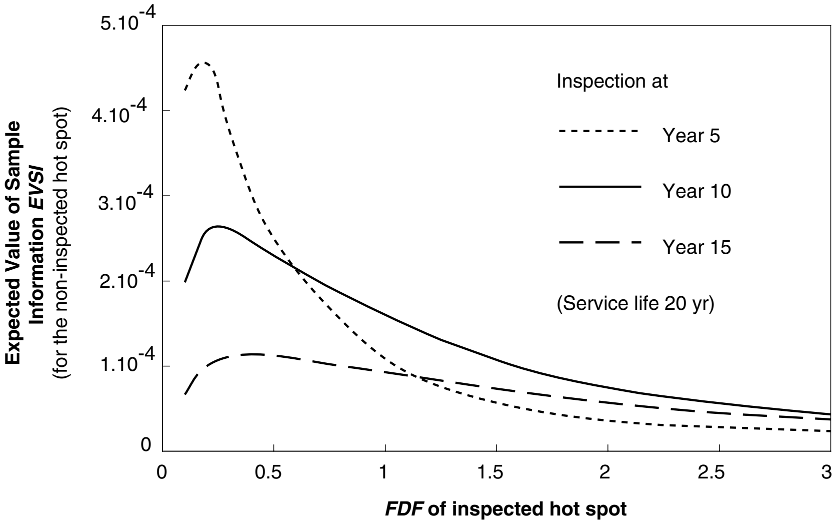

Fig. 7. The expected value of information for a hot spot (*FDF* = 2), by inspection of a dependent hot spot; from Straub and Faber [32].

If the system consists of several hot spots, the EVSI from one inspection is obtained by summing up the benefits for all non-inspected hot spots B_1 to B_n. When several hot spots are inspected, the EVSI is evaluated accordingly, although with increased computation efforts, because the number of possible combinations of inspection outcomes increases quadratically with the number of considered inspections. Fig. 8 illustrates the EVSI from inspecting n_{Insp} hot spots with equal *FDF*s. Regarding the inspection time and the *FDF* of the inspected hot spots, the same observations are made as in Fig. 7: Whereas the information obtained by earlier inspections has a higher (net present) value, inspecting hot spots with lower *FDF*s gives more information. As can be demonstrated by decision analysis [36], by increasing n_{Insp} the EVSI approaches asymptotically the expected value of perfect information (EVPI), which corresponds to knowing the true value of the *FDF* of the non-inspected hot spot. Once the EVPI is reached, every additional inspection can only provide information about the state of the inspected hot spot itself, but not about the system anymore.[9] Accordingly, the maximum information on the system which can be acquired by inspections in year 10 is independent of the *FDF* of the inspected hot spots; the difference between the two curves therefore diminishes for increasing inspection coverage. In Fig. 8, the EVPI is approached already after few inspections, but it should be noted that this is caused by the very low values of the *FDF*, which are not typical for most structures.

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[9] This upper limit of obtainable information is also observed in the concept of the system PoD (probability of detection), introduced in [35]. The system PoD applies a simple adaptive decision model to determine the relation between inspection coverage and the fraction of defects identified.

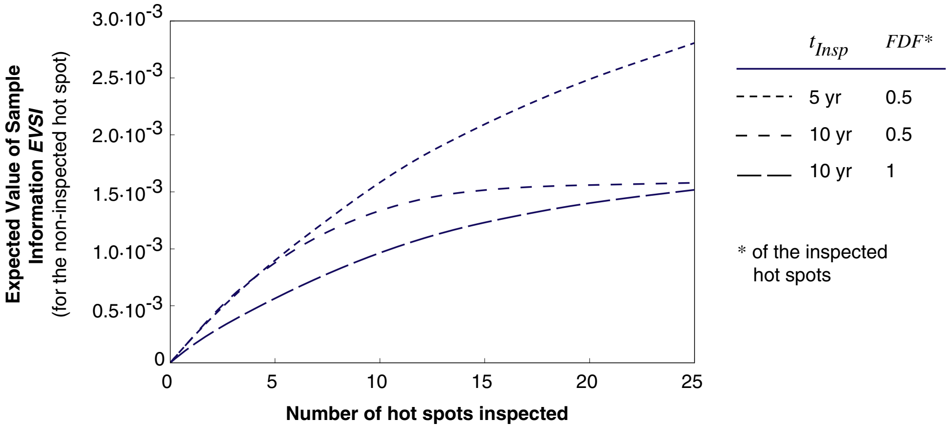

Fig. 8. The expected value of information for a hot spot ($FDF = 2$) from inspecting n_{Insp} dependent hot spots in the system at time t_{Insp}.

8. Planning of inspections for the entire system

As previously noted in Section 6.2, at present it does not appear feasible to simplify the general decision tree for systems in a similar way as for single hot spots. This signifies that the entire decision tree must be evaluated. Such a decision tree contains a very large number of branches which is prohibitive for the direct evaluation of the full decision tree. However, based on the previously introduced concept it is possible to evaluate the full decision tree in an approximate and adaptive way, and thereby taking advantage of the generic approach to RBI.

It is proposed to start by the optimisation of the inspection efforts for the individual hot spots and to subsequently introduce the system. When comparing the optimisation for individual hot spots with the optimisation for the entire system, the value of information of an inspection with respect to the entire system is essential. It has been noted that the value of this information is always equal to or larger than zero. Therefore, the benefit of an inspection cannot be lower when taking the system into account, as compared to the optimisation for the individual hot spot. It follows that a priori the inclusion of the entire system in the analysis can only increase the optimal inspection effort! A posteriori, after the first inspections have been performed, the optimal inspection effort in some cases can decrease when accounting for the system, but only if the inspections result in less detected defects than expected. If the dependencies between the hot spot performances are not accounted for, the resulting inspection effort is thus always lower than the optimal one. An additional rule is that in a group of hot spots with the same degree of inter-dependencies and the same failure consequences, the hot spots with the lowest reliability should always be inspected first. These considerations lead to the proposal of the following simplified procedure:

A. Prior to the detailed analysis, in accordance with Section 2, the critical deterioration mechanisms and the potential locations of failure, the hot spots are identified. All hot spots are then characterised by their generic parameters (the respective values of the influencing parameters) such as the *FDF*, the geometrical and the loading properties.

B. In addition to the traditional analysis, the dependencies between the parameters at the different hot spots must be estimated. The hot spots are then arranged in groups with large inter-dependencies (such groups are typically defined by their location in the structure and /or by the detail type). Each group is then considered separately in the following.
C. If a generic database is not already available, it must be established, covering the relevant deterioration mechanisms and parameter ranges. An additional routine, which performs the updating of the *FDF*s based on the inspection results at dependent hot spots, must be computed following Straub and Faber [32].
D. The inspection planning is now carried out for the individual hot spots taking into account the dependency of the inspection cost on the total number of inspected hot spots and accounting for the redundancy of the system with respect to hot spot failure. This is straightforward and computationally inexpensive when applying the generic RBI.
E. A first inspection campaign is planned when the first hot spots are due for inspection according to their individual inspection plan. In many instances it is beneficial to perform inspections, which are required one year later, during the same inspection campaign, because of the reduced marginal inspection costs.
F. In systems with a large number of hot spots, it can be beneficial to reduce the number of inspections in the campaign: If the inspection results are better than expected, the required inspection effort for the not yet inspected hot spots is reduced and the omitted inspections can be postponed to the next inspection campaign. Theoretically is possible to determine the optimal reduction, however, such an approach appears not feasible at present because of the required computational efforts. Instead, the reduction in the number of inspections within one campaign can be made based on semi-quantitative considerations regarding the number of inspections needed for an overview of the system performance, as presented in [16,35]. These semi-quantitative considerations are related to the number of inspections required to approach the EVPI as discussed in Section 7.1.
G. After the inspections are performed, the *FDF*s of all hot spots (inspected and non-inspected) are updated.
H. With the new *FDF*s, the inspection plans for the individual hot spots are recalculated. The procedure is then continued with point E until the end of service life is reached.

This simplified procedure leads to sub-optimal solutions, because the value of information concept is not explicitly included in the analysis. The final determination of the number of inspections, although following a consistent procedure, is based on a semi-empirical procedure. On the other hand, the updating of the inspection plans with the results from the inspection of the other hot spots in the system is fully quantitative, i.e., after inspections have been performed, the hot spot models with the updated *FDF*s represent the full information available. The procedure is therefore a reasonable trade-off between accuracy and applicability.

For some structural systems, the above procedure fails. These are systems with a large number of hot spots, where the reliability of the hot spots is very high and/or where the cost of failure of the hot spots is low. This is outlined in the following.

Ship structures typically contain a large number of fatigue hot spots and failure of individual hot spots is generally not critical due to the large redundancy in the system. When considering only individual hot spots, the resulting inspection strategy would be to not perform any inspection at all. Therefore, for systems with a large number of hot spots and a high degree of redundancy, instead of inspecting few hot spots using NDE it is generally more promising to visually inspect larger parts of the system or to use inexpensive techniques like flooded member detection, see, e.g. [41]. In such cases, the dependency between the hot spot performances is only of importance in determining the amount of redundancy in the system (large dependencies reduce the redundancy), but not for the value of information. The redundancy is the most important parameter when determining the inspection frequency in such systems.

The individual hot spots in pipelines can have large reliabilities (when corrosion is considered, individual hot spots correspond to sections of the pipes whose size will depend on the correlation length of the considered corrosion mechanism). Although an individual hot spot failure may cause significant damage, inspecting an individual hot spot is often not economical if the system, i.e., the dependencies between the hot spot performances, is not considered. However, in view of the entire system such inspections would be highly beneficial because they provide information on the state of the system. In such cases, the value of information concept allows to determine the optimal number of inspections at a given inspection time. Consider a pipeline consisting of 100 hot spots, all of which have high reliabilities, so that the individual inspection plans demand no inspections at all. When the value of information from n_{Insp} inspections with respect to the total system is calculated, this can be compared with the cost of inspections and the optimal number of inspections can be determined, see [32] for a numerical example.

In addition to the discussed solutions, a new approach for controlling the deterioration in structural systems as described above is proposed, namely the installation of hot spots with a low resistance, which have a good accessibility and which have no influence on the system performance. These hot spots could serve as indicators for the system and could be regularly inspected or monitored. Using the concept outlined in Section 7, the optimal design of such "indicator hot spots" can be determined, together with an optimal inspection scheme. Such indicators should be designed to give the maximum information on the other hot spots in the system. From Fig. 7, it is observed that these indicators should have a very low *FDF* to give the most information. The generic parameters of all hot spots in the system are then automatically updated based on these inspection or monitoring results. If the deterioration in the system is larger than expected, the inspections of the indicator hot spots will reduce the *FDF*s of all hot spots and can in this way trigger further actions on the other hot spots.

9. Conclusions

In past publications dealing with RBI for structural systems, the term "system effects" has been used, in analogy to many other reliability problems, see [42]. This denotation indicates that the system is considered in addition to the individual components, which in the context of RBI are the hot spots. Such a bottom-up approach is also followed in the present paper. It allows maintaining the advantages of RBI for single hot spots, namely the use of a consistent decision modelling combined with fully quantitative inspection and deterioration models, while at the same time facilitating the application on large structural systems.

The application of RBI to structural systems is enhanced by developments in two directions. One cornerstone is the increase in the computational efficiency in the calculation of the inspection plans for the individual hot spots, as achieved through the use of the generic RBI, which is shortly reviewed in the paper. The second cornerstone, which is presented in detail, is the modelling of the different statistical and functional dependencies in the system and their effects on the inspection and maintenance decisions. The different dependencies in a structural system are discussed in general and a special focus is put on the dependencies in the deterioration at the individual hot spots together with an analysis of the different types of decisions related to inspection and maintenance in structural systems.

It is found that for many structures, especially for those subject to fatigue, inspection decisions should optimally be made in an adaptive way. It is then shown how the Bayesian decision analysis can be applied to determine the value of the obtained information at an inspection in such systems. This value of information is essential for many applications, because it quantifies the benefit of an inspection for the entire system and thus characterises an important feature of the RBI for structural systems. As an example, it is shown how it allows to determine the optimal design of so-called indicator hot spots which work similar to an alarm system for deterioration failures in the system. It is observed that the complexity of the decision problems impedes a full optimisation of the inspection efforts taking into account all dependencies in the system. Therefore, a pragmatic yet consistent approach to RBI for structural systems is proposed: The proposed procedure for updating all hot spots in the system after an inspection is combined with simple rules that are based on the insights from the value-of-information concept.

Methods, such as those presented in this paper, are commonly confronted with the somewhat imprecise reproach of being “too theoretical”. Underlying this are two arguments, which are often well-justified, namely that the methods are computationally too demanding and thus not economical and that the methods are too difficult too understand and may therefore cause gross errors. For large structural systems, the procedures proposed in this paper have a large potential benefit for optimising the inspection and maintenance efforts, which quickly exceeds the cost of establishing a database containing the generic inspection plans and a software for the application of the procedure on a daily basis. The second argument is more severe, but it is reminded that the procedures presented in this paper must be embedded in a general asset integrity management strategy, which considers all possible failure modes. As discussed in [41], such strategies must be robust in regard to the underlying model assumptions.

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