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A risk analysis for asset management considering climate change

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Abstract

This paper presents an optimization framework for highway infrastructure elements that integrates risk profiles (for infrastructures) and economic aspects. One main goal is to assess the necessary additional effort to satisfy performance constraints under different scenarios of climate change. In order to be easily deployable by national road administrations (NRAs), this framework is built in such a way that it can be embedded into asset management systems that include an inventory of the asset, inspection strategies (to report element conditions and safety defects) and decision-making for funds allocation. Using the inventory of the asset and condition assessment as input, the method aims to determine some degradation profiles for bridge components, retaining walls and steep embankments. The method to determine the degradation process is detailed so that any infrastructure manager can determine their own deterioration processes based on the inventory and condition assessment of their stock. Combining degradation of highway infrastructures with a risk analysis, this paper presents an optimization framework to determine optimal management strategies.

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Keywords: risk analysis; optimization; condition rating; highway infrastructures

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1. Introduction

Several road infrastructures built in Europe during the 1960s and the 1970s are now in need of repairs or can no longer adequately serve the road user. As infrastructure deterioration caused by heavy traffic and an aggressive environment becomes increasingly significant, this results in a higher frequency of repairs and higher costs to maintain the required service life performance of road infrastructure. In a context of climate change under scare capital resources (PIARC 2008, 2011, 2012a,b), the need for risk-based assessments to prioritize risk and optimize budgets/resources for maximized service life performance of road infrastructure is increasingly urgent. This paper aims at presenting an overall approach which considers some performance aspects in the decision process for ageing structures (such as structural degradation, increasing loads, and natural hazards, translated into risk profiles).

The proposed framework is summarized in Fig. 1. Module M1 is concerned with degradation modelling and considers ageing, traffic volume and environmental conditions as potential factors in the degradation process, Module M2 considers an integrated risk analysis, and finally Module M3 considers maintenance strategy optimization.

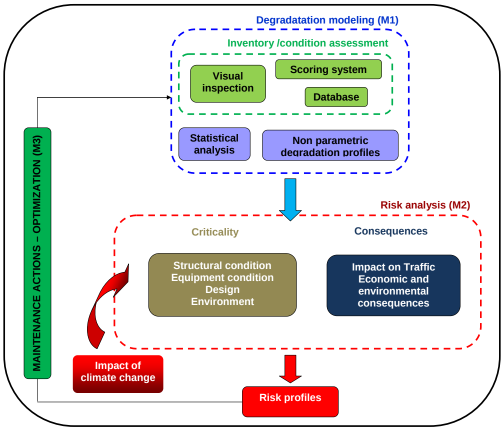

Fig. 1. Proposed risk-management framework.

This framework, developed in the project RE-GEN (Risk assEssment of aGEing iNfrastructure) funded through the CEDR Transnational Road Research Programme Call 2013 “Ageing Infrastructure”, includes (a) the modelling of vulnerability considering climate change, (b) traffic effect forecasting, (c) risk profiling and (d) risk management and decision tools. The objective of this project is to provide Road Owners/Managers with best practice tools and methodologies for risk assessment of critical infrastructure elements, such as bridges, retaining structures and steep embankments. The output of the RE-GEN project should be a risk modelling tool, which will consider risk from a variety of perspectives, e.g. safety risk, financial risk, operational risk, commercial risk and reputational risk, considering both the current situation and the challenges posed by projected traffic growth, climate change and limited funding.

This paper, which focuses on climate change and impact in the determination of optimal strategies, is organized as follows. The methodology to model degradation due to the ageing process (Module 1 in Fig. 1) is described in section 2. Using the inventory of the asset and condition assessment as input, the method aims to determine some degradation profiles for bridge components, retaining walls and steep embankments depending on the age of the infrastructure, traffic volume or environmental conditions. Section 3 details the risk analysis (module 2 in Fig. 1), based on the degradation model which also includes potential effects of climate change and traffic growth. Once the degradation profiles are determined, they are used to characterize how the vulnerability of infrastructures evolves with time. Different types of hazards are then considered (including the potential impact of climate change) and risk is defined as a joint measure of hazards, vulnerability and consequences of failure. The two following failure modes are considered in this paper: (i) loss of serviceability (minor structural failure or equipment failures that need some urgent repair actions), (ii) structural failure (major structural failure that need some urgent major rehabilitation). These failure modes are influenced first of all by the ageing process that will be considered through the introduction of degradation matrices of infrastructure components. Climate change and traffic load increase of traffic will also affect these degradation matrices. Section 4 details the optimization procedure (module 3 in Fig. 1) which is at the core of asset management principles. Optimal management strategies, based on the consequences of possible actions on the future condition of the system, will be determined through an optimization process which considers uncertainty. The aim is to minimize the maintenance costs while minimizing the level of risk and maximizing the performance of the infrastructure. Such optimization procedures should allow NRAs to assess the necessary additional effort to satisfy performance constraints under different scenarios of traffic growth and climate change.

2. Condition prediction

As mentioned in the introduction, the objective of the proposed framework is to deliver an asset management framework based on visual inspection. To do so, some stochastic Markov chains are used for predicting the performance of infrastructure components (Lounis 2003). Some explanations on Markov chains are briefly summarized below. The example of the French scoring system (see Table 1) is detailed below for illustration. The IQOA scoring system (quality assessment of engineering structures), used in France on the non-concessionary state managed national roadway network, is an example of an approach to provide a global assessment of the road infrastructures at a national level (Orcesi & Cremona 2010). It is noted that the method to determine the degradation process is detailed so that any infrastructure manager can determine their own deterioration processes based on the inventory and condition assessment of their stock.

Table 1. IQOA scoring system.

Score	Apparent condition
1	Good overall state
2	Equipment failures or minor structure damage. Non urgent maintenance needed
2E	Equipment failures or minor structure damage. Urgent maintenance needed
3	Structure deterioration. Non urgent maintenance needed
3U	Serious structure deterioration. Urgent maintenance needed

Considering a database with scores between years a_0 and a_f, the probability $P_b(q_1, q_2)$ of a component b weighted a characteristic value (e.g. the deck or wall area) to move from score q_1 to score q_2, is defined as the total area rated q_1 at year i and q_2 at year $i+1$ divided by the total area rated q_1 at year i, for i between a_0 and a_f. This probability is expressed as

$$P_b(q_1, q_2) = \frac{\sum_{i=a_0}^{a_f-1}\left(\sum_{k=1}^{n_{q_{1,i}\to q_{2,i+1}}} A^k_{q_{1,i}\to q_{2,i+1}}\right)}{\sum_{i=a_0}^{a_f-1}\left(\sum_{k=1}^{n_{q_{1,i}}} A^k_{q_{1,i}}\right)} \quad (1)$$

where $n_{q_{1,i}}$ = number of components rated q_1 at year i, $n_{q_{1,i}\to q_{2,i+1}}$ = number of components moving from score q_1 to score q_2 between year i and year $i+1$, $A^k_{q_{1,i}}$ = area associated with component k scored q_1 at year i and $A^k_{q_{1,i}\to q_{2,i+1}}$ = area associated with component k moving from score q_1 to score q_2 between year i and year $i+1$. In matrix $\boldsymbol{P}_b$, the element in row k and column l represents the probability for component b weighted by 1 m^2 of area to move from score k to score l in one year. Once transition probabilities are determined, the objective is to quantify the performance of each bridge/retaining wall component through the use of an adequate lifetime indicator.

This indicator is determined herein by the probability for a component to be scored in a certain condition with time. If (i) the probability of a component q_b^i to be quoted in any score is known at year i (for example, after a visual inspection of the bridge) and stored in a vector q_b^i and (ii) the associated homogeneous markov chain, associated with a transition matrix $\boldsymbol{P}_b$, is determined, the probability at year $i+1$ is given by the following equation:

$$\boldsymbol{q}_b^{i+1} = \boldsymbol{q}_b^i \boldsymbol{P}_b \tag{2}$$

Assuming a homogeneous Markovian process, the scoring probability can then be forecasted if the transition matrix and the initial probability vector are known. The potential impacts of climate change and ageing of infrastructures are modeled through the combination of several degradation matrices for different ranges of age of bridges, walls and slopes. These degradation matrices can be determined for different national assets, depending on the availability of scoring system database.

3. Risk analysis

3.1. Failure modes

The aim herein is to make a clear link between the degradation of components and the risk profiles. Such risk profiles quantify a joint measure of hazards, vulnerability and consequences of inadequate level of service considering several failure modes. Risk levels are time dependent since performance of structures is decreasing with time due to progressive deterioration of the infrastructure components. As mentioned in the introduction it is proposed to consider the two following failure modes:

- loss of serviceability (minor structural failure or equipment failures that need some urgent repair actions),
- structural failure (major structural failure that needs some urgent major rehabilitation).

To do so, a system analysis is performed to determine a performance indicator at a system level. Indeed, an infrastructure consists of several components and each component has its own failure probability, the interaction between components determines the overall failure probability of an infrastructure. Therefore, there is a need to develop a systematic method to evaluate the system-level failure probability considering the interaction of different system components. In the proposed approach, two groups of components are considered: the structural ones and the equipments ones. In the particular case of the French condition scoring system for bridges, several components are visited among which : bridge deck, expansion joints, waterproofing layer, bearings, and equipments.

The components visited for walls are: the zone of influence (defined as the area behind the retaining wall to a line rising 45 degrees from the top edge of the footing), sewerage/drainage, equipments, structural condition. The fault tree used in the RE-GEN project to switch from a component level to a system level is illustrated in Figs. 2(a) and 2(b) for bridges (for failure modes 1 and 2, respectively) and in Figs. 3(a) and 3(b) for walls (for failure modes 1 and 2, respectively). All the fault trees shown in these figures correspond to a series system in which the failure state is reached if a least one of the components fails.

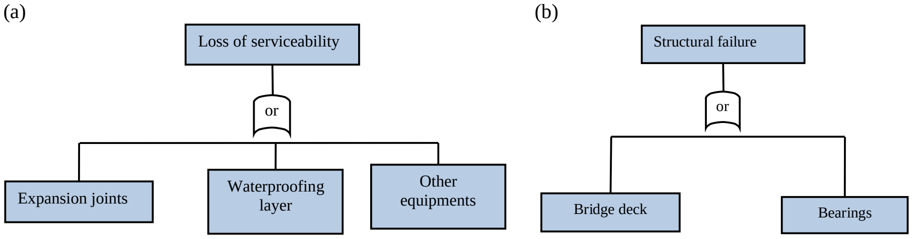

Fig. 2. Fault tree model for (a) loss of serviceability and (b) structural failure (for bridges).

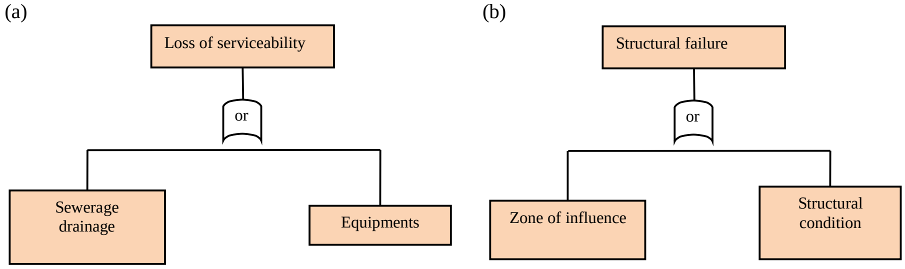

Fig. 3. Fault tree model for (a) loss of serviceability and (b) structural failure (for walls).

For bridges and walls, condition scores are assessed for equipment condition or structural condition by considering the worst score shown in the corresponding fault tree. Tables 2 and 3 give an example on how new annual transition sequences can be built from the existing database.

Table 2. Identification of annual transition sequences for worst scores among equipments.

Score	2010	2011	2012	2013	2014
Expansion joint	1	2	2	2	2E
Waterproofing layer	1	1	1	1	1
Other equipments	2	2	2E	2	2
Series "Equipment" system	2	2	2E	2	2E

Table 3. Identification of annual transition sequences for worst scores among structural components.

Score	2010	2011	2012	2013	2014
Bearings	1	1	1	3	3U
Deck	1	1	2	2E	2E
Series "structural" system	1	1	2	3	3U

To determine the annual transition matrix associated to equipment and structural components, the new sequences identified with the approach exemplified in Tables 2 and 3 are used (and not the initial database anymore). The probability of failure is finally associated with the probability to be in the worst condition class (i.e. 2E for the equipment-component system and 3U for the structural-component system). Moreover, all sequences associated with an improvement of the condition (due to maintenance actions) are replaced by some degradation in the subsequent score, considering that the components would have deteriorated by one score if no maintenance had been performed. Such an assumption leads to a pure degradation matrix. An example of matrix built on a sample of the database for prestressed concrete bridges is provided in Eq. 3

$$\boldsymbol{P_s} = \begin{pmatrix} 0.74 & 0.19 & 0.06 & 0.01 & 0 \\ 0 & 0.89 & 0.10 & 0.01 & 0 \\ 0 & 0 & 0.91 & 0.09 & 0 \\ 0 & 0 & 0 & 0.94 & 0.06 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \qquad \boldsymbol{P_e} = \begin{pmatrix} 0.80 & 0.17 & 0.03 \\ 0 & 0.88 & 0.12 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

For such a degradation model, the criticality level can be associated with the probability to be in each of the different condition classes for the different components. For example, when considering the loss of serviceability, the criticality level can be defined as the probability to be in 2E (urgent equipment maintenance needed). For failure mode related to structural failure, the criticality level can be defined as the probability to be in 3U. Let us then introduce some consequence classes associated with the considered failure modes. Considering the condition inventory of the infrastructure stock and information on traffic volume on each structure, it is possible to assess the overall volume of traffic corresponding to each condition score (1, 2, 2E, 3 and 3U). This traffic volume is distributed every year in each of the condition scores and the probability to be in each condition state evolves with time due to degradation (see sections 2 and 3.1). It is then possible (i) to assess the distribution of traffic according to the distribution of condition scores at the scale of the infrastructure stock, and (ii) to translate the volume of traffic associated with a certain condition score into some delay costs if the access to these infrastructures is limited. In the case of the failure modes “Loss of serviceability” and “structural failure”. The consequence classes are 2E (for the series equipment system) and 3U (for the series structural system). The intersection of criticality and consequences enables us to quantify the risk at the scale of the infrastructure stock. Considering the two failure modes above, two risk functions noted $LR_s(i)$ and $LR_e(i)$ for each year i of the time horizon can be defined, respectively, and are used in section 4 in the optimization process.

3.2. Introduction of climate change effects into the scoring system

Once the degradation model is built, it is expected to deliver for climate change exceptional degradation matrices that suddenly deteriorate the component to the worst condition and may lead to a major structural failure of some part of the structure or even to the full collapse. The objective of the methodology detailed below is then to (i) indicate how each component is more or less affected by each extreme event, and (ii) help assess the consequences associated with each impact on critical parts of the structure.

It is important to note that these additional degradation matrices are not there to model a change in the degradation rate each year (let’s say for carbonation) due to the temperature/CO$_2$ concentration increase. Instead, they model the occurrence of a sudden event (storm, flood, heavy rains...) that results from climate change and for which we will control the frequency of occurrence and the % of the stock affected by this event. The matrices $\boldsymbol{CM}_1$ to $\boldsymbol{CM}_4$ introduced in Eq. 4 are applied to a percentage of the infrastructure asset and with a certain frequency (depending on optimistic to pessimistic scenarios of climate change) in addition to the annual degradation matrices exemplified in Eq. 3 (the three first rows and columns of matrices $\boldsymbol{CM}_1$ and $\boldsymbol{CM}_2$ being considered and noted $\boldsymbol{CM}_1^*$ and $\boldsymbol{CM}_2^*$ when applied to the series equipment system).

$$\boldsymbol{CM}_1 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad \boldsymbol{CM}_2 = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad \boldsymbol{CM}_3 = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad \boldsymbol{CM}_4 = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (4)$$

Then, $x_{\boldsymbol{CM}_i}\boldsymbol{CM}_i\boldsymbol{P_s}$ (respectively $x_{\boldsymbol{CM}_i^*}\boldsymbol{CM}_i^*\boldsymbol{P_e}$) is applied every τ_i (respectively τ_i^*) on series structure system (respectively series equipment system), where $x_{\boldsymbol{CM}_i}$ and $x_{\boldsymbol{CM}_i^*}$ represent intensity coefficients in the sense that they stand for a percentage of the asset submitted to exceptional events, and τ_i and τ_i^* represent the frequency of corresponding exceptional events. $\boldsymbol{CM}_1$ is a “low scenario”: a component scored 2 will move to 2E. This first scenario will then exacerbate equipment defects but does not have any impact on the structure (e.g. heavy wind). $\boldsymbol{CM}_2$ is very similar to scenario $\boldsymbol{CM}_1$, the only difference being that components scored in 1 are also affected by the event. $\boldsymbol{CM}_3$ is a medium scenario: a component scored in 1 or 2 moves in 2E, and a component scored in 2E moves to 3. So an event that suddenly deteriorates equipment and which confirms the transition to 3 for a component which was scored 2E before the event and which was already close to move to a state with some issues on structure (e.g. sea level rise, medium floods). Finally, $\boldsymbol{CM}_4$ is a “severe” scenario: sudden deterioration in worst score (disastrous floods, landslide for walls). Intensity coefficients and frequency of the events can be associated with each matrix in Eq. 4 to characterize optimistic to pessimistic scenarios. Some values are provided in section 4.3 for illustration.

4. Integration of risk analysis into asset management

4.1. Maintenance strategies

Several prospective scenarios can be defined in the proposed framework (Orcesi et al. 2015). These scenarios can give priority either to preventive or corrective actions, or both, with the aim of controlling the budget and ensuring the preservation of the asset. Each degradation/maintenance strategy is associated with a transition matrix. For example in the case of prestressed concrete bridges, the current degradation matrices $\boldsymbol{S_{1,s}}$ and $\boldsymbol{S_{1,e}}$ are respectively associated with the matrix $\boldsymbol{P_s}$ for the series structural system and with matrix $\boldsymbol{P_e}$ for the series equipment system (see Eq. 3). If the objective of another strategy is systematically to upgrade scores i to j, the term (i,j) of the transition matrix is fixed at 1 and other terms in the *ith* row of the corresponding matrix are set to 0. The transition matrices that enhance repair actions for structure and equipment are

$$\boldsymbol{S_{2,s}} = \begin{pmatrix} 0.74 & 0.19 & 0.06 & 0.01 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix} \quad \boldsymbol{S_{2,e}} = \begin{pmatrix} 0.80 & 0.17 & 0.03 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \tag{5}$$

If another strategy is systematically to restore infrastructures to the “as new” condition, then the associated transition matrices (for structure and equipment) are assumed to be:

$$\boldsymbol{S_{3,s}} = \begin{pmatrix} 0.74 & 0.19 & 0.06 & 0.01 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix} \quad \boldsymbol{S_{3,e}} = \begin{pmatrix} 0.80 & 0.17 & 0.03 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \tag{6}$$

Similar transition matrices for various strategies can be defined for other bridge or retaining walls components and can be used in the optimization process described in section 4.2.

4.2. Optimization framework

The ultimate step of the framework in Fig. 1 integrates performance aspects in the decision process for ageing structures (including structural degradation, increasing loads, and natural hazards, translated into risk profiles). The variables in the optimization process are the maintenance actions and times on bridge, walls, slopes. Optimal parameters are those that minimize the overall risk while minimizing the maintenance costs.

Such optimization procedures should allow NRAs to assess the necessary additional effort to satisfy performance constraints under different scenarios of traffic growth and climate change.

The objective of this framework, based on that proposed by Orcesi & Cremona (2011), is to determine the optimal annual combination of the different strategies to maintain the bridge stock in good condition with limited budgets. A new challenge herein is to include the effects of climate change in the procedure and to see how it impacts financial allocation in a long-term perspective.

The corresponding procedure is detailed hereafter for the structural series system (the subscribe s is omitted for the sake of clarity).

Each year $i = 1, \ldots, n-1$, where $n =$ number of years considered in the maintenance planning, a vector $\boldsymbol{X}^i_{\mathbb{S}_j} = {}^t\begin{pmatrix} x^i_{\mathbb{S}_j,1} & x^i_{\mathbb{S}_j,2} & x^i_{\mathbb{S}_j,2E} & x^i_{\mathbb{S}_j,3} & x^i_{\mathbb{S}_j,3U} \end{pmatrix}$ is associated with the strategy $\mathbb{S}_j$. The term $\boldsymbol{X}^i_{\mathbb{S}_j}(k) = x^i_{\mathbb{S}_j,k}$ represents the proportion of bridges scored k for which strategy $\mathbb{S}_j$ is applied at year i. The vector $\boldsymbol{q}^{i+1}$ at year $i+1$ is obtained from that at year i as follows

$$\boldsymbol{q}^{i+1} = \boldsymbol{q}^i \boldsymbol{M}_i \qquad \forall i = 1, \ldots, n-1 \tag{7}$$

where

$$\boldsymbol{M}_i = \sum_{j=1}^{m} \begin{pmatrix} x^i_{\mathbb{S}_j,1} & & 0 \\ & \ddots & \\ 0 & & x^i_{\mathbb{S}_j,3U} \end{pmatrix} \boldsymbol{S}_j \tag{8}$$

and $m =$ number of possible transition matrices, with constraint that

$$\sum_{j=1}^{m} x^i_{\mathbb{S}_j,k} = 1 \qquad \forall i = 1, \ldots, n-1, \forall k \in \{1, 2, 2E, 3, 3U\} \tag{9}$$

In Eq. 8, $\boldsymbol{S}_j$ can represent not only the various maintenance scenarios considered by the owner, but also the exceptional degradation matrices due to climate change (see Section 3.2). The fractions $x^i_{\mathbb{S}_j,k}$ associated with such additional degradation will serve as control parameters to test different assumptions of climate change/traffic increase scenarios (pessimistic, mean, optimistic) and will not be used as variables in the optimization process.

Conversely, the fractions $x^i_{\mathbb{S}_j,k}$ associated with decisions of the owner will be the variables in the optimization process. They will be determined in such a way that the condition of the bridge/retaining wall component remains above a minimal threshold and that the costs are as low as possible. The constraint on $x^i_{\mathbb{S}_j,k}$ ensures that, taking into account the fraction of bridges that are analyzed, the final matrix $\boldsymbol{M}_i$ verifies the property

$$\sum_{q=1}^{5} \boldsymbol{M}_i(p,q) = 1 \qquad \forall i = 1, \ldots, n-1, \ \forall p = 1, \ldots, 5 \tag{10}$$

Each strategy $\mathbb{S}_j$ (a strategy $\mathbb{S}_j$ is entirely defined by the associated transition matrix $\boldsymbol{S}_j$, as previously mentioned) is associated with a cost vector $\boldsymbol{C}_{\mathbb{S}_j} = {}^t\begin{pmatrix} c_{\mathbb{S}_j,1} & c_{\mathbb{S}_j,2} & c_{\mathbb{S}_j,2E} & c_{\mathbb{S}_j,3} & c_{\mathbb{S}_j,3U} \end{pmatrix}$ where the *kth* element of $\boldsymbol{C}_{\mathbb{S}_j}$ ($k \in \{1, 2, 2E, 3, 3U\}$) is

$$\boldsymbol{C}_{\mathbb{S}_j}(k) = \left\langle \begin{pmatrix} \delta_{1,k} & \delta_{2,k} & \delta_{2E,k} & \delta_{3,k} & \delta_{3U,k} \end{pmatrix} \boldsymbol{S}_j, \begin{pmatrix} \delta_{1,k} & \delta_{2,k} & \delta_{2E,k} & \delta_{3,k} & \delta_{3U,k} \end{pmatrix} \boldsymbol{C} \right\rangle \tag{11}$$

and where $\mathbb{S}_j =$ *jth* strategy matrix ($j = 1$ or 2 herein), $\langle .;. \rangle =$ scalar product notation, and $\delta_{l,k} =$ Kronecker function.

The annual cost for the structural series system

$$C_{a,s}(i) = A_T \sum_{j=1}^{m} \sum_{k \in K} \boldsymbol{X}^i_{\mathbb{S}_j}(k) \boldsymbol{C}_{\mathbb{S}_j}(k) q^i_k \tag{12}$$

is the sum of all the costs from the different strategies for each year i, where $k \in \{1, 2, 2E, 3, 3U\}$, $\boldsymbol{X}_{\mathbb{S}_j}^{i}(k) =$ fraction of bridges with score k concerned by strategy $\mathbb{S}_j$ at year i, $\boldsymbol{C}_{\mathbb{S}_j}(k) =$ cost of the strategy $\mathbb{S}_j$ for bridge/retaining wall component scored k and $q_k^i =$ percentage of the component scored k at year i.

A procedure similar to that described in Eq. 7–12 enables to calculate the annual cost $C_{a,e}(i)$ for the equipment series system. Several optimization scenarios are possible. The first one, detailed in Eqs 11(a–c), consists in minimizing simultaneously the total maintenance cost and the risk cumulated during the planning horizon:

$$\text{Find} \qquad \boldsymbol{X}_{\mathbb{S}_j}^{i} \qquad \forall j = 1,...,m, \forall i = 1,...,n-1 \tag{13a}$$

$$\text{to} \qquad \text{Minimize} \sum_{i=1}^{n-1} \left(C_{a,s}(i) + C_{a,e}(i) \right) \tag{13b}$$

$$\text{and} \qquad \text{Minimize} \sum_{i=1}^{n-1} \left(LR_s(i) + LR_e(i) \right) \tag{13b}$$

$$\text{such that} \qquad LP > LP_0 \qquad i = 1 \ldots n \tag{13c}$$

where LP stands for the level of performance (for example some thresholds for percentage in each of condition scores), and $n =$ number of years in the planning.

4.3. Optimization results

Several methods exist to solve the optimization problem in Eq. 13. The algorithms are generally referred to as constrained nonlinear optimization or nonlinear programming. They attempt to find a constrained minimum of a scalar function of several variables starting at an initial estimate. Genetic algorithms can also be used, in particular when several objective functions are considered (criteria to be minimized or maximized). In particular, NSGA-II (Non-dominated Sorting in Genetic Algorithms) program developed by Deb et al. (2002) can be used to find optimal solutions set of multi-objective optimization problem. The fitness assignment scheme of NSGA-II consists in sorting the population in different fronts using the non-domination order relation. To form the next generation, the algorithm combines the current population and its offspring generated with the standard crossover and mutation operators. Finally, the best individuals in terms of non-dominance and diversity can be chosen in the set of optimal solutions called Pareto solutions. From this set, the decision maker can choose the best possible compromise among available financial resources, necessary safety and condition levels, and acceptable levels of structural deterioration. An example of optimal Pareto solutions is shown in Fig. 4, for a time horizon fixed at 30 years. Three scenarios “optimistic”, “mean”, and “pessimistic” are considered in this figure for illustration. The performance constraints to be respected each year i over the n years of the time horizon are as follows: $\%1 > 0.55$, $\%2 + 2E < 0.30$, $\%3 + 3U < 0.15$ and $\%3U(i) < \%3U(0) - (3U(0) - 1\%)\, i/n$. The intensity and frequency coefficients are provided in Table 4. Obviously, it is shown in Fig. 4 that maintenance cost and risk increase with intensities and frequencies of extreme events which have a direct impact on the overall condition of the asset.

Table 4. Coefficients considered for intensity and frequency of extreme events (see section 3.2).

Coefficients	Optimistic	Mean	Pessimistic
$x_{\boldsymbol{CM}_1}$; τ_1	0 ; -	0 ; -	0 ; -
$x_{\boldsymbol{CM}_2}$; τ_2	0 ; -	10 ; 5%	7 ; 5%
$x_{\boldsymbol{CM}_3}$; τ_3	0 ; -	15 ; 1%	10 ; 1%
$x_{\boldsymbol{CM}_1^*}$; τ_1^*	0 ; -	7 ; 5%	5 ; 5%
$x_{\boldsymbol{CM}_2^*}$; τ_2^*	0 ; -	10 ; 5%	7 ; 5%

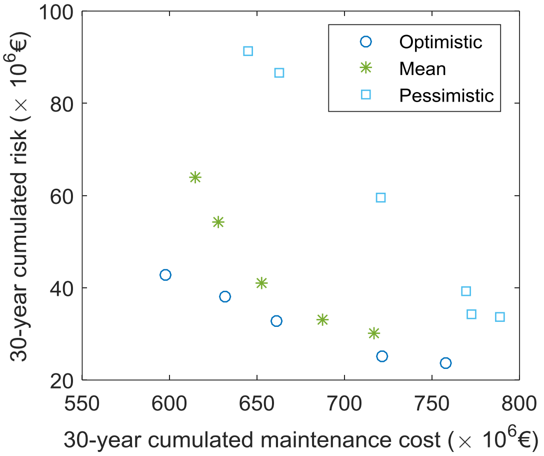

Fig. 4. Pareto Fronts obtained with optimistic, mean and pessimistic scenarios (see Table 4).

4. Conclusions

The proposed optimization framework enables to consider risk from a variety of perspectives, e.g. safety risk, financial risk, operational risk, commercial risk and reputational risk, considering both the current situation and the challenges posed by climate change and limited funding. This framework is based on visual inspections (e.g., condition rating) and it is expected to use it to determine optimal asset management strategies for bridges, retaining walls and steep embankments depending on the age of the infrastructure, traffic volume or environmental conditions.

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