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Understanding Risk Factors

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Re-Gen
Risk Assessment of Ageing Infrastructure

Final report on optimization of management strategies under different traffic, climate change and financial scenarios

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risk assessment of ageing infrastructure

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Executive summary

An efficient and well-maintained transportation system is a fundamental factor for the economic and social developments, as it allows the quick, safe and easy exchange of passengers and freight. This mobility is mostly sustained via a network of roads and highways providing high level of service and flexibility. To maintain a high quality of service, there is a significant need for tools which allow national road administrations (NRAs) to better manage their infrastructures.

Bridges, retaining structures, and steep embankments are significant critical infrastructure components in terms of safety and functionality for the whole transportation infrastructure. The ageing and deterioration of these components exacerbated by climate change from one hand and the increasing traffic intensities and loads from the other hand make them the bottlenecks of the transportation infrastructure. The inconveniences (congestions) created by upgrading and repairing activities are growing rapidly with increasing traffic and age.

Decisions about the replacement or repair of these infrastructures, as well as when and how to repair each infrastructure are common and among difficult management issues for asset managers. In particular, asset management systems are employed to manage transportation infrastructure and help guide policy makers.

The present report (i) details the main components of current asset management tools, (ii) proposes an optimization framework for the management of highway infrastructure elements, integrating risk profiles (for infrastructures) and economic aspects, and (iii) summarizes the main results on the optimization of management strategies under different traffic, climate change and financial scenarios.

One main objective is to assess the necessity of additional efforts to satisfy performance constraints under different scenarios of climate change/traffic growth. In order to be easily deployable by NRAs, the developed framework is capable of being embedded into asset management systems that include an inventory of the asset, inspection strategies (to report component conditions and safety defects), and decision-making for fund allocation.

1 Introduction

The majority of infrastructure components for road transport system were constructed during the 1960's and the 1970's, and many of the structures built during this period are now in need of repairs or no longer can adequately serve the road users. As infrastructures age, deterioration caused by heavy traffic and an aggressive environment becomes increasingly significant, resulting in a higher frequency of repairs and possibly a reduced load carrying capacity. The need for safe effective asset management to maintain environmentally friendly traffic routes is increasingly urgent.

Asset management systems have been developed by many countries to serve as a tool to track inventory data and to analyze maintenance and improvement needs for existing infrastructures. These systems aim to combine management, engineering, and economic input in order to help determine the best action to take for the management of all structure elements of the network over time. The actions can involve enhancement of safety, providing additional structural capacity, and preservation of existing facilities.

In the context of climate change under scarce capital resources (PIARC 2011), the need for risk-based prioritization and optimization of budgets/resources for maximized service life performance of road infrastructure seems urgent. This report is aimed at presenting an overall approach, considering performance aspects such as structural degradation, increasing loads, and natural hazards in the decision making process for management of ageing structures.

The framework proposed in the Re-Gen project is summarized in Fig. 1, where 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, while module M3 considers maintenance strategy optimization.

In this report:

(i) A review of asset management practices is conducted to describe and illustrate the main modules of asset management systems.

(ii) A methodology is developed to model degradation due to the ageing process (module M1 in Fig. 1). Using the inventory of the assets and condition assessment as input, the method aims to determine degradation profiles for bridge components, retaining walls and steep embankments, depending on the age of the infrastructure, traffic volume and environmental conditions. This approach is illustrated via data extracted from highway infrastructure assets in Ireland, Denmark and France.

(iii) A risk analysis (module M2 in Fig. 1) is performed, based on the degradation model, considering potential effects of climate change and traffic growth. Once the degradation profiles are determined, they are used to characterize how the vulnerability of the infrastructures evolves over time. Different types of hazards are considered (including the potential impact of climate change), while the risk is defined as a joint function of hazards, vulnerability, and the consequences of failures. The two following failure modes are considered: (i) loss of serviceability (minor structural failures or equipment failures that need some urgent repair actions), (ii) structural failures (major structural failures that need urgent major rehabilitation). These failure modes are influenced mainly by the ageing process that will be considered through the introduction of degradation matrices of infrastructure components. Climate change and traffic load increase will also be considered in the degradation matrices.

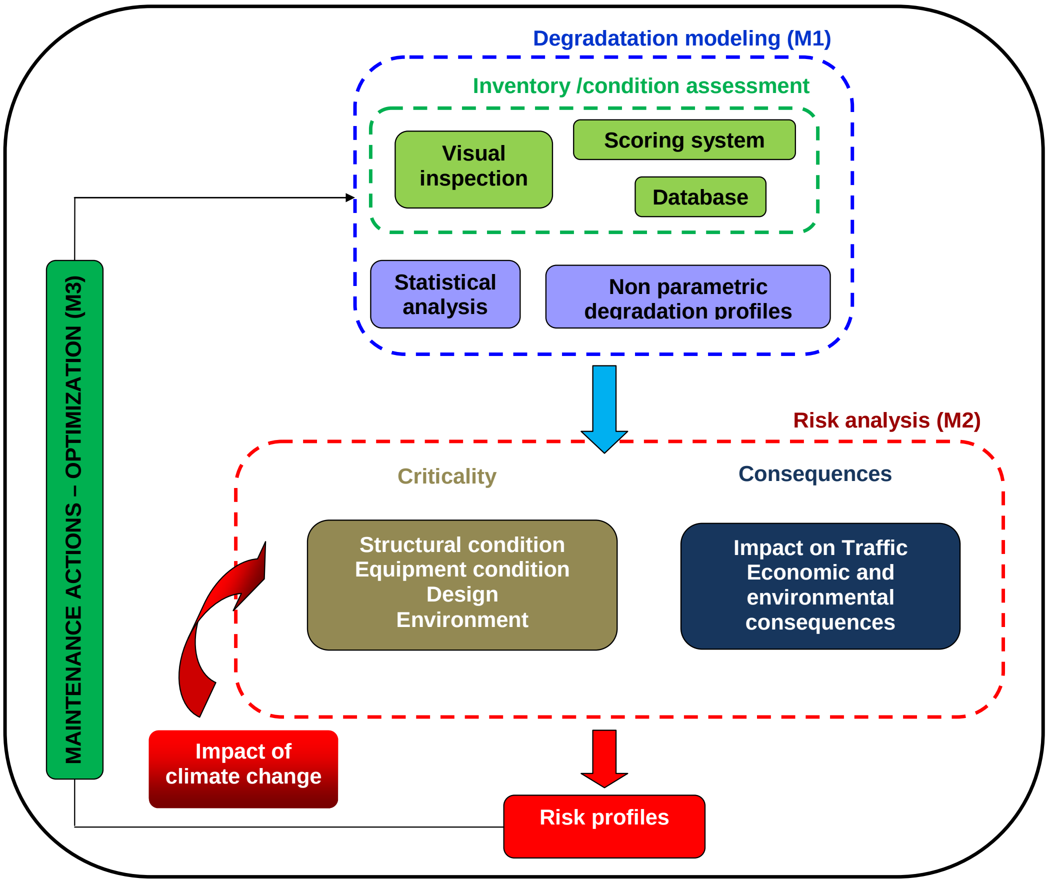


Figure 1. Proposed risk-management framework.

(iv) An optimization procedure (module 3 in Fig. 1) which is at the core of asset management principles is presented. Mono and multi-objective optimization processes are explained in detail. Optimal management strategies, based on the impacts of possible actions on the future condition of the system, are determined through an optimization process while considering uncertainty. The aim is to minimize the maintenance costs while minimizing the level of risk and maximizing the performance of the infrastructure. Such an optimization process should allow NRAs to assess the necessary additional efforts to satisfy performance constraints under different scenarios of traffic growth and climate change.

(v) We present the results of the optimization procedure and highlight the significance of considering risk-based costs, quality constraints, traffic growth, and climate change in the optimization problem. This section shows results of both mono and multi-objective scenarios, and also illustrates cost forecasting while considering uncertainties in the model parameters.

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 under the impact of climate change, (b) consideration of potential impacts of traffic growth, (c) risk assessment and (d) risk management and development of decision tools. The objective is to provide road owners/managers with the best practice tools and methodologies for risk assessment of critical infrastructure elements, such as bridges, retaining structures, and steep embankments. The proposed methodology can consider risk from a variety of perspectives, e.g. safety risk, financial risk, operational risk, commercial risk and reputational risk, while considering both the current situation and the challenges posed by projected traffic growth, climate change and limited funding.

2 Asset management concepts

2.1 What is asset management?

Asset management is aimed at integrating finance, planning, engineering, personnel, and information in order to assist agencies in cost-effective managing of assets (AASHTO 1997a, FHWA 2007). In its broadest sense, asset management is defined as “a systematic process of maintaining, upgrading, and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organized and flexible approach to making the decisions necessary to achieve the public’s expectations” (OECD 2001).

The aim of an asset management system is to assist the road network administration in the process of planning and optimizing the operation, maintenance, repair, rehabilitation and replacement of the network and its assets (pavement, bridges, tunnels, equipment etc.) in the most cost-effective way in the long run while minimizing the consequences of traffic disturbances during road works (PIARC 2005).

Ultimately the key objective of asset management is to improve decision-making processes for allocating funds among an agency’s assets so that the best return of investment can be obtained. To achieve this goal, asset management embraces all of the processes, tools, and data required to manage assets effectively (Nemmers 2004). For this reason, asset management is also defined as “a process of resource allocation and utilization” (AASHTO 2002).

Fig. 2 illustrates the strategic asset management framework within which jurisdictions may select their priorities for improving their approach to road management (PIARC 2005).

Figure 2. Asset management framework.

As indicated in (PIARC 2005), “a particular jurisdiction may select to concentrate on administrative reforms in terms of organizational changes or contracting-out arrangements. Others may wish to concentrate on implementation of specific tools, such as pavement management systems, bridge management systems, and effective asset performance measures.

2.2 What belongs to road assets?

The road assets usually contain (PIARC 2005):

- roads (substructure, running surface, equipment and accessories, etc.),
- bridges,
- other structures (retaining walls, embankments, tunnels, sewer equipment, rain water systems, etc.),
- road areas (including rest areas, parking areas and loading areas),
- unfinished road projects and structures.

The road network is generally divided into several parts based on the respective economic lifetimes. This is because bridges, for example, are designed to be in service for much longer than pavements, and so the economic lifetimes used for these items are different.

2.3 Components of an asset management system

An asset management system undertakes several procedures to enhance different components, tools, and activities. Asset management systems provide decision makers with tools for evaluating probable effects of alternative decisions. These tools develop decision support information from quantitative data regarding the agency's resources, current condition of physical assets, and an estimation of their current value.

More specifically, a typical asset management system consists of various modules (Fig. 2) including (PIARC 2004a):

- inventory – to establish basic parameters at the network level to identify infrastructure dimensions, material types, location, ownership, etc.,
- inspection – to report structures element conditions and safety defects,
- appraisal – to evaluate structural capacity, functionality, etc.,
- budget – to assist managers in allocating funds for maintenance and repair work,
- preservation – to establish policies for maintaining road network elements,
- project planning – to assist in preparing project priorities and tracking accomplishments,
- execution,
- history and documentation.

The modules shown in Fig. 3 are described below, as it is proposed in PIARC (2004b).

<u>Goals, Policies and Budget</u>

Asset management is a goal-driven management process. To manage assets effectively, the decision-making process must be aligned with the agency's goals, objectives, and policies. Goals are expressed in terms of objectives to be met over the planning horizon (e.g. the extent of the maximum traffic congestion, demands on safety, demands on intermodal interactions, demands on general customer satisfaction, etc.). Policies are developed to provide the necessary framework to support achieving target objectives. Policies regarding engineering standards, economic development, community interaction, political issues, administration rules, and the agency's organizational structure influence asset management components. Finally, how the budget is allocated for the road network or individual assets represents the third pillar of an asset management framework, including the total budget allocated annually or multi-annually for the entire network as well as each division.

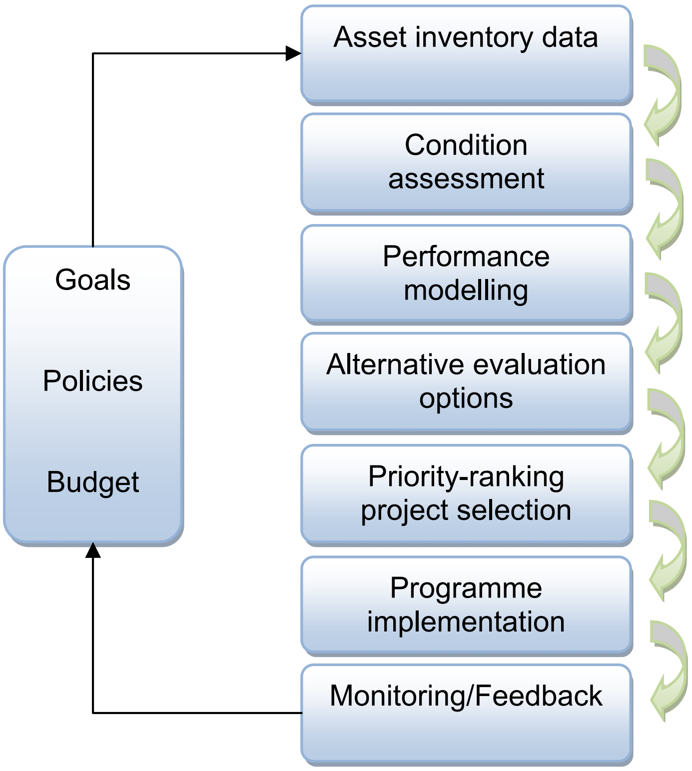


Figure 3. Components of an asset management (PIARC 2004b).

Asset Inventory Data

The asset inventory contains information about physical location, characteristics (e.g. basic documents relevant for the structure, drawings, dimensions), usage, work history, work planned, costs, resources, and any other information considered relevant by the agency. Additional information provided by asset management systems may include financial reports about the agency's assets, showing both the current economic value and the future asset value estimates. Decisions regarding the type and amount of data to be collected are made based on the agency's needs for decision support and available resources.

Condition Assessment

A knowledge of current condition is needed to assess future maintenance/rehabilitation needs. Condition assessment is expressed in terms of performance measures selected by the agency. These performance measures should be the ones used by the agency to establish objectives. Condition indices, percentage of the network system rated in good condition, and remaining life of the asset network are some examples of performance measures used for physical assets.

Performance Modeling

Performance models are used to predict future scenarios for the asset network. Projecting the asset network condition over the planning horizon serves to identify future funding needs. Appropriate selection of performance models is essential to an effective asset management system. The selection of performance models is based on the types of assets being managed and the data available in the agency's data inventory to support the models. It is noted that in many national road agencies, performance models are handled outside the systems, and only the results are implemented in the systems afterwards.

Alternative evaluation options

Program analysis implies studying different alternatives that may be feasible for implementation. Analytical tools are developed to assist agencies in evaluating the implications of different investment scenarios and work plan strategies. “What if” analysis is usually performed to assess the impact of alternative management decisions. This type of analysis is difficult, if not impossible, without the assistance of analytical tools. Analytical tools to assist evaluating alternative decisions may involve simulation, life-cycle costing, cost-benefit analysis, database query, optimization, risk analysis, and other methodologies. Decision-support tools to assist an agency’s personnel in identifying needs and comparing investment alternatives are essential in the asset management process.

Priority-ranking project selection

Project-selection criteria should be established to assist in the selection of the best group of projects. Having criteria for project selection implies having methods of identifying both short- and long-term effects expected from projects. Methods of prioritizing work activities and selecting projects are based on economic techniques, but social and political factors should also be considered in the criteria.

Program Implementation

The implementation program must address every aspect of the management process. Procedures for goal review, policy review, data collection, data storage, data access, condition assessment, budget development, construction, maintenance, monitoring, and feedback should be considered in the implementation program. The implementation program should involve all management levels that participate in the decision-making process. The implementation of an asset management approach in the programming and budgeting cycle requires continuous encouragement from upper management as well as commitment from all personnel involved. In practice, an asset management approach can only succeed if it supports the agency management process efficiently. The effectiveness of an asset management approach should be reflected in savings to the agency. However, these benefits can only be achieved if the agency ensures that the asset management system is properly used at all management levels.

Monitoring/Feedback

Feedback is an essential activity to maximize the agency’s benefits from an asset management system. The asset management system should be capable of incorporating lessons learned from monitoring the ongoing process. Goals, objectives, and the agency’s policies may be adjusted based on feedback from implementation. However, great care should be taken before modifying core components of the system. Major modifications to the system, including changes in database requirements, prediction models, economic analysis techniques, and reporting tools, should be carefully evaluated. Minor changes that simplify the flow of information in the process are preferred. Particularly preferred are those changes that provide better means of accomplishing the agency’s objectives without disturbing ongoing activities.

2.4 Risk analysis considering climate change

Several risks related to climate change have been recently highlighted (CEDR 2012, PIARC 2012b, 2013), showing how climate change may have significant impacts on society. One main characteristic of climate change is the dealing with an uncertain future in the sense that the decisions which are obvious under present conditions may become less certain if conditions change. Such perspectives justify the use of a risk analysis which should include additional hazards and consequence evaluation.

In particular, a probable increase of winter precipitation in western, northern and central Europe could generally lead to higher operational costs (snow clearing and salting), requiring improved emergency plans, winter maintenance guidelines and traffic safety measures (Petkovic & Thordarson 2012). PIARC (2013) analyzes effects such as de-icer consumption, manpower and costs, based on Intergovernmental panel on climate change (IPCC) scenarios. This report describes impacts on infrastructures, specifically considering frost/thaw cycles. Increased snow fall (both amount and intensity) raises the risk of avalanches and may yield higher investments in protective installations. Norway and other member countries point out the need to develop better tools for predicting, alerting, and analyzing the risk of landslides and avalanches (Petkovic & Thordarson 2012). Finally, climate change is likely to threaten people living in delta areas all over the world. Rising sea levels, combined with increased variability in river discharge and precipitation, increase the risk of floods and droughts.

In this context, Conference of European Road Directors (CEDR) initiated work on studying the effects of climate change on roads. The work belonged to Strategic Plan 2 (2009-2013), and is organized as twin tasks dealing with adaptation on one hand (task 16) and mitigation of climate change on the other hand (task 17). In link with this strategic plan, Petkovic & Thordarson (2012) indicate that "a substantial decrease of summer precipitation, combined with an increase of temperature, in southern and central Europe will directly lead to more severe and prolonged drought periods, possibly introducing a risk of more frequent wildfires in new areas. In the entire Europe, and especially in some regions in northern Europe, there is a risk of increase in the intensity of daily precipitation and the probability of extreme precipitation events. This may cause more frequent flooding in existing drainage systems due to insufficient capacity. It may also cause erosion and landslides, a risk pointed out by all the member countries (Petkovic & Thordarson 2012). Adaptation of guidelines for the design of appropriate culverts, drains, bridges, erosion and landslide protections will be necessary. Problems due to stronger winds or storms are generally not considered as very severe by the member states of this task group. Roads in coastal areas are at risk from anticipated changes in sea level. Especially Sweden, Norway, Denmark and France report concern for existing low-lying road sections, ferry berths and sub-sea tunnel portals. Beside the need for a better analysis of probable sea levels, design guidelines for sea defences against wave erosion will have to be adapted and implemented."

The CSIRO project "*Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure*", funded by both Department of Climate Change and Energy Efficiency (DCCEE) and CSIRO Climate Adaptation Flagship, makes theoretical and practical advances in analysing climate change impacts on the deterioration of concrete infrastructure (Wang et al. 2010a-d). In particular, some tools have been developed to simulate impacts of climate change on carbonation and corrosion through penetration of chloride in existing concrete. This approach considers environmental variables and their uncertainties, such as the concentration of carbon dioxide, yearly mean temperature and relative humidity as well as material properties. Both chloride-induced and carbonation-induced corrosion show the potential experience of a scalable impact of climate change, which should be considered for maintenance planning. Adaptation options should also be developed and optimised both to mitigate the impact and to enhance the adaptive capacity of concrete structures subject to changing climate. A number of climate change adaptation options were simulated to determine their effectiveness. This included five options to reduce chloride-induced corrosion such as electrochemical chloride extraction, polyurethane sealer, polymer-modified cementious coating, cover replacement and cathodic protection. It also included two options to reduce carbonation-induced corrosion, that is, re-alkalisation and cover replacement.

In addition to such theoretical analyses, the RIMAROCC project (RIMAROCC, 2009) lists a certain number of risk management decision tools used in Europe in the realm of climate change:

1. The Deltares approach is used for spatial planning and to design water management systems. The approach starts from the perspective of the decision maker. The climate change scenarios are not the starting points, but the requirements of key water management issues (or any other sector, e.g. road) on the climate state. The approach starts with an assessment of how much climate changes can be accommodated by the sector's management strategy and what magnitude of changes can cause problems. This can be considered a sensitivity analysis of the sector. It provides an overview of the vulnerability of the sector's management strategy to climate change.
2. The GERICI project for infrastructures, France: Egis (international group offering engineering, project structuring and operations services) has developed GERICI: a Climate Risk Analysis and Management Approach and Model for Infrastructures. GERICI is a GIS model for measuring the vulnerability of all sensitive components of an infrastructure. Initially the study was conducted on a motorway. On the basis of a socio-economic analysis, GERICI provides assistance to the authorities concerned in structuring and establishing priorities for the investments. In the case of the forecast or announcement of an exceptional event, definition of the scenario can be initiated to take the most relevant emergency measures in collaboration with the other partners, including the emergency services.
3. Guidelines in the United Kingdom: The Highways Agency has recognised the need to ensure an effective strategic road network in the context of a changing climate. Therefore a Climate Change Adaptation Strategy has been developed, and in support of this strategy the Highways Agency Adaptation Strategy Model (HAASM) (Highways Agency, 2008). The HAASM provides a systematic process to (i) identify the activities of the Highways Agency that will be affected by a changing climate; (ii) determine associated risks and opportunities; and (iii) identify preferred options to systematically address them.
4. Within the Nordic Road Association (NVF) (www.nvfnorden.org), a survey has been carried out to investigate the effects of climate change on the road maintenance. The work was carried out mainly between the years 2004 and 2006 and focused on a risk analysis, i.e., the probability of a certain event and is the magnitude of the consequence. Probability is seen in a national perspective, i.e., the total number of events that occur in the country. Consequences are costs incurred to road owners and users. The time perspective of the project spans from today's climate to expected changes until 2040. The probabilities and consequences are assessed with the assumption that no preventive actions are taken. A side effect of the national perspective is that some impacts of climate change may not be seen in the results, e.g. the reduced cost for less snow clearance in the south may be disappeared with the increased cost for snow clearance in the north. (NVF, working group 41. 2008-03-25, working material). The result of the survey is presented in the form of a matrix where the impact of climate change and extreme weather on the risks of unwanted events is measured for each country using color codes (Figs 4 and 5).

Prob.	Description	Once in:
1	Extremely small	100 yr
2	Very small	25-100 yr
3	Small	10-25 yr
4	Some	1-10 yr
5	Reliable	Yearly
Cons.	Description	Cost
1	Very small	<10MSEK
2	Small	10-50MSEK
3	Large	50-100MSEK
4	Very large	100-500 MSEK
5	Catastrophic	>500 MSEK

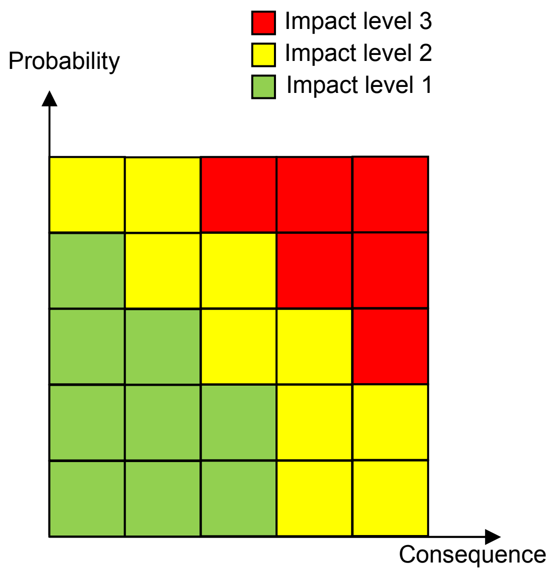


Figure 4. Risk matrix used to sort the climate change-induced events according to their level of impact (NVF, working group 41. 2008-03-25, working material).

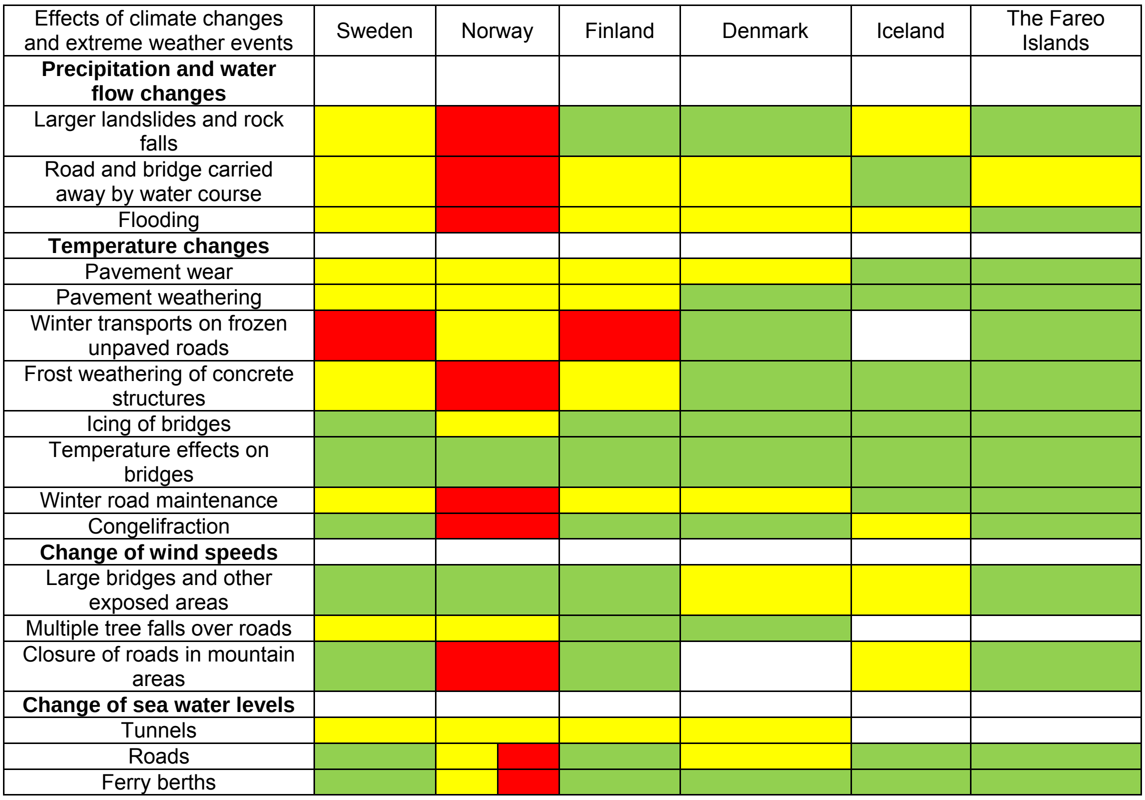


Figure 5. Risk analysis of impacts of climate change and extreme weather in the Nordic countries (NVF, working group 41. 2008-03-25, working material).

3 Ageing process

3.1 *Knowledge from inspection strategies*

To determine which infrastructure requires maintenance, it is necessary to undertake systematic inspections. One of the main purposes of such inspections is to provide data on those structures that are in a poor or critical condition and in need of repair, strengthening or rehabilitation. The results of these periodic inspections are used to provide an assessment of the condition of both the structural elements and the structure itself (BRIME, 2001). If the data is correctly stored in a computer database, it is then possible to extract some useful information, especially to predict future degradation.
Notwithstanding that road infrastructure inspection activities across Europe can vary from country to country (i.e. different location, weather, type of bridges that require different frequency of inspection actions), it is still possible to define common types and frequencies of inspections. The definition and the aim of each type of inspection are (SBRI 2013a, b):

<u>Routine or annual</u>

A visual observation based on specific standard forms/check lists. The aim is to detect minor damage that can be promptly repaired. The team is formed by one or two members of the maintenance staff with specific training.

<u>Main, principal or periodic special</u>

A detailed visual inspection performed with specific inspection units for access. The aim is to confirm the initial/last/latest condition rating and to help define the need for repair actions. Damage such as crack openings, damaged concrete, and exposed corroded rebar are marked on the bridge. The team is led by an engineer or experienced person in bridge inspection.

<u>Special, extra or exceptional detailed</u>

A more detailed inspection is carried out when:

a) A repair plan is needed for the complete rehabilitation of the bridge;
b) A specific damage needs to be assessed which occurred as a result of natural hazards, vehicle collision, etc.

Non-destructive/destructive tests are used together with laboratory analysis. The results of the tests help evaluate the damage conditions and allow recommendations for repair. The aim is to assess the infrastructure’s condition or to define the cause of a specific damage and thus to set a rehabilitation strategy. The team is led by an engineer or experienced person in bridge inspection (min. Five years).
The following subsections provide a non-exhaustive overview of some scoring systems which are used in European countries in which condition ratings are introduced to characterize the condition of structural/non-structural infrastructure components.

3.1.1 *Scoring system in France*

The IQOA scoring system (quality assessment of engineering structures), used in France on the non-concessionary state to manage national roadway network, is an example of an approach for global assessment of the road infrastructures at a national level. The national bridge/walls stock is assessed every 3 years (i.e., by applying IQOA inspections annually on 1/3 of the total number of assets (Orcesi & Cremona 2011). This 3-year inspection process is part of a more general inspection framework that also includes annual routine inspections and the 6 years detailed inspection program, as explained in milestone M5.1 (Orcesi, 2014).

During an IQOA inspection, several components are inspected: equipments (pavements, footways, cornices, expansion joints, etc.), protecting components (waterproofing layers, anticorrosion coating, etc.) and structural components (deck, supports, bearings, foundations, etc.). By using catalogs of defects, the inspectors are able to provide a score for each particular component and structural part as shown in Table 1 . A global score is then defined as the worst score of all the components.

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

The differences between defects represented by scores 2 and 2E and scores 3 and 3U are substantial. Scores 2 and 2E represent serviceability defects, while scores 3 and 3U represent structural deficiencies. The main objective of such a tool is to provide a snapshot of individual bridge/wall conditions, and thus a snapshot of the overall bridge/wall stock quality (by aggregating all the IQOA scores).

3.1.2 Scoring system in Denmark

The Danish Road Directorate uses the DANBRO database system for the management of the bridge stock on highways and motorways. The condition is evaluated for 15 standard components of a bridge structure, one of which refers to the general condition of the bridge, as shown in Table 2. Table 2 indicates all those bridge components which have to be considered in the evaluation of a bridge structure condition.

Table 2. Bridge components considered in the evaluation process of condition

Component	Description
1	Bridge in general
2	Wing walls (wing walls and possible retaining walls)
3	Slopes (slopes with slope protection, adjacent to the abutments and wing walls)
4	Abutments (abutment structure with back wall, bridge seat, visible parts of the footings)
5	Piers
6	Bearings (bearings on abutments and piers)
7	Slab
8	Waterproofing
9	Girders/beams (main girders, cross beams, diaphragms, bracings,.)
10	Parapet/railing (parapets, guard rails and railings)
11	Bridge surface (normally the surface between the curbs)
12	Crossing passage
13	Expansion joints (all components of expansion joints including special overlays adjacent to the joint)
14	Drainage system
15	Other elements (bridge components, which are not included in the previous mentioned 12 components)

The extent of damage, or 'condition', of each component is estimated on site, if possible with the help of geometry data from the inventory. A condition rating is then assigned. This is a numerical value which describes the condition of the observed component of the bridge structure. A description of the condition ratings is given in Table 3.

After the conditions of all components are evaluated, the condition of the whole bridge can be assessed accordingly. As a result, the highest (most unfavorable) condition rating in a component-level is not necessarily the condition rating of the whole structure. The final assessment of the structure should identify the damaged components, the type and extent of the damage, expected progression of the damage and its influence on the traffic flow and safety. The general rule is that the condition rating for the whole bridge cannot be higher than the condition rating of the most deteriorated component and cannot be lower than the condition ratings of the main components, like abutments, piers, bearings, slabs and girders.

Table 3. Scoring system in Denmark and Ireland.

Score	Apparent condition
0	No or insignificant damage
1	Small damage but no need of repair except routine maintenance
2	Some damage, repair needed when convenient. Component is still functioning as originally designed
3	Significant damage, repair needed very soon
4	Serious damage, immediate repair needed
5	Ultimate damage, total failure or risk of total failure of the component

3.1.3 Scoring system in Ireland

In Ireland, the EIRSPAN bridge management system was introduced in 2001 to coordinate and integrate activities such as inspections, repairs and rehabilitation work of bridges to ensure optimal management of the national road structure stock. Prior to the implementation of EIRSPAN no centralised system of bridge management had existed in Ireland on either national or non-national roads. Responsibility for bridge management rested with the individual local authorities and, inevitably, it differed considerably from one local authority to another (Duffy, 2004). The system includes the management of bridges equal to or greater than 2·0 m total skew span on the national primary and secondary road networks. Further information on the system can be found in Duffy (2004) or at http://www.tii.ie/

The management system used in Ireland, EIRSPAN, is a customized version of the DANBRO system to suit Irish practice (Duffy, 2004). For example, a section was included to facilitate the incorporation of data of masonry arch bridges, which makes up to approximately 40% of the bridges on the Irish national roads. The system was also expanded to encompass the NRA's Technical Approvals process.

3.1.4 Scoring system in Slovenia

In Slovenia, the condition of a bridge is expressed by the condition rating for every main bridge component and for the entire bridge (Slovene regulations 1987, Terčelj et al. 1988), the latter being simply the sum of all the components' condition ratings. In Table 4, the main components of a bridge to be considered in bridge rating and their main constituent parts are given.

The condition rating R for quantitatively assessing the condition of a bridge and its components is expressed by the following function:

$$R = \sum V_D = \sum B_i K_{1i} K_{2i} K_{3i} K_{4i} \quad (1)$$

where:

- V_D - damage type value (unit?).
- B_i - basic value associated with the damage type i.
  The value of B_i is within the range of 1 to 4 and expresses the potential effect of the damage type on the safety and/or durability of the observed structural element.
- K_{1i} - Factor which describes the extent of the damage.
  This is expressed by numerical values between 0 and 1. The description usually refers to one or more components of the bridge or to the whole bridge structure. The extent of the damage on the affected component or structure is not described by the measured sizes (length, area, etc.)..
- K_{2i} - Factor which describes the intensity of the damage.
  It is expressed by values between 0 and 1. The description of intensity is usually related to the type of damage (e.g. width of the cracks, thickness of the delamination, etc).
- K_{3i} - Factor which describes the importance of the structural component or member for the safety of the entire structure.
  The values range between 0 and 1.
- K_{4i} - Factor which describes the urgency of intervention.
  The values range between 0 and 10. The chosen value depends of the type of structure, and seriousness and risk of collapse of the affected structure or its part.

Table 4. Main bridge components considered in the Slovenian

Component	Description
Substructure	Landscape around bridge structure, riverbed, foundations, supporting members
Superstructure	Superstructure, tunnel
Bridge surface	Bridge surface
Bridge equipment	Bearings, expansion-joints, safety equipment, drainage system

According to the obtained value of condition rating R, the bridge structure is classified into one of five condition classes, Table 5. Based on this rating, the main bridge inspector will ultimately make a decision about the global condition class of the whole bridge structure. It is noted that this method for condition rating was improved in 1998 (Znidarič & Perus, 1998).

Table 5. Condition classes for bridge structure used in Slovenia

Condition class	Definition	Condition rating R
1	Critical	>20
2	Bad	14-22
3	Satisfactory	8-17
4	Good	3-12
5	Very good	0-5

3.2 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, a stochastic Markov chain approach is used for predicting the performance of infrastructure components. The examples of the French (used in France on the non-concessionary state managed national roadway network), Danish and Irish scoring systems (see Tables 1 and 3) are detailed in this section for illustration. Such scoring systems are examples of an approach to provide a global assessment of road infrastructures at a national level. Two methods are provided to determine transition matrices: the first one (section 3.2.1) uses the breakdown per age and per condition state at the scale of the overall stock. The second one (section 3.2.2) considers transition sequences in the inspection database. It should be noted that these two methods to determine the degradation process are detailed so that any infrastructure manager can determine their own deterioration processes based on their inventory and the condition assessment of their stock. The second one considers transition occurrences for each structure in the database during a certain period of time.

3.2.1 Approach based on the breakdown per age and per condition state

The approach proposed in this section can be used to determine transition matrices from an inspection database. Instead of considering each element and corresponding transition occurrence in the database, the overall breakdown in condition states with age is considered. The main assumption is that the categorization of the different states for each age is the same as the one which would be observed during the i*th* inspection of the stock. This method can be applied to inspection database (Odent et al., 1999) once the classification according to the age and condition is known. The main advantage of such an approach is in the case of recent scoring systems with only one or two inspection campaigns (that is, when there is few transition occurrences between some scores), or when the time interval between two inspections is fluctuating.

A constrained optimization procedure is then used to determine the transition matrix $\boldsymbol{P_b}$ (as in Equation 2, $\boldsymbol{P_b}(i,j)$ is the probability to move from state i to state j). The i*th* term of the sum given in Equation 2 represents the error between the real state at the inspection $i+1$ and the condition $i+1$ calculated by the model. The sum over *n* instants given in Eq. 2 is the total of the errors at each step and the aim is to minimize this error:

$$\begin{cases} \min\limits_{P \in M_5} \sum\limits_{i=1}^{n} \left\| {}^t\boldsymbol{q}(i+1) - {}^t\boldsymbol{P_b}\ {}^t\boldsymbol{q}(i) \right\| \text{ such that :} \\ \forall i,\ \forall j,\ \boldsymbol{P_b}(i,j) \in [0,1] \\ \forall i,\ \sum\limits_{j} \boldsymbol{P_b}(i,j) = 1 \end{cases} \tag{2}$$

Kuhn-Tucker equations can be used to solve this nonlinear problem. These equations are necessary conditions to ensure the feasibility of a non-linear problem. They are often used in this type of problem (Bazaraa et al., 1992). To obtain pure degradation, free of any maintenance strategy, each term in row i and column j under the main diagonal is set to 0, and its previous value is added either to the diagonal term (row i and column i) or to the subsequent one (row i and column $i+1$). The new transition matrix is then a theoretical deterioration matrix reflecting a zero intervention strategy that in the first case gives a slightly optimistic view as infrastructures that receive no interventions are not supposed to deteriorate further, or that considers that the component would have deteriorated by one unit in the second case.

3.2.2 Approach based on transition occurrences

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 by a characteristic value (e.g., the deck or wall area) moving from score q_1 to score q_2 can be defined as the total characteristic unit (area, length, width, etc.) rated q_1 at year i and q_2 at year $i+1$ divided by the total characteristic unit rated q_1 at year i, for i between a_0 and a_f. This probability is expressed as:

$$P_b(q_1,q_2) = \frac{\sum_{i=a_0}^{a_f-1}\left(\sum_{k=1}^{n_{q_{1,i}\to q_{2,i+1}}} A^k_{q_{1,i}\to q_{2,i+1}}\right)}{\sum_{i=a_0}^{a_f-1}\left(\sum_{k=1}^{n_{q_{1,i}}} A^k_{q_{1,i}}\right)} \tag{3}$$

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 of bridge deck with component k moving from score q_1 to score q_2 between year i and year $i+1$.

Applying this approach is relevant if several inspection campaigns exist in the database with regular inspection intervals. To obtain pure degradation matrices, all sequences associated with a condition improvement (due to maintenance) are replaced by some degradation in subsequent scores, considering several possible assumptions. For example, whether the components would or would not have deteriorated by one unit if no maintenance had been performed. Such assumptions lead to a pure degradation matrix.

3.2.3 Condition forecasting

In matrix $\boldsymbol{P_b}$, the element in row k and column l represents the probability of the component b weighted by 1 m^2 of area to moving from score k to score l in one year. Once the 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 of a component to be scored in a certain condition with time. If (i) the probability of a component 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 $\boldsymbol{q}_b^i$ 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:

$$\boldsymbol{q}_b^{i+1} = \boldsymbol{q}_b^i \boldsymbol{P_b} \tag{4}$$

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.

4 Towards risk analysis

4.1 General concepts

In the context of climate change resulting in an increased frequency of extreme weather conditions and with an expected increase of traffic, a risk-based approach is proposed for identifying and qualifying hazards and quantifying vulnerability and consequences. Such an approach can be applied to existing structures while several years of operation, distresses, or characteristics may increase their vulnerability, and reduce their level of service and the safety of users.#The aim herein is to make a clear relationship 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 the performance of structures is decreasing with time due to progressive deterioration of the infrastructure components. Two following failure modes are considered:#

- 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: structural components (transition matrix $\boldsymbol{P_s}$) and equipment (transition matrix $\boldsymbol{P_e}$).

Let us consider the scoring system used in France for illustration (five condition classes: 1, 2, 2E, 3, 3U for each component of the structure) and introduce some consequence classes associated with the considered failure modes. Considering the condition inventory of the infrastructure stock and the 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 section 3.2). 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 $LR_s(i)$ and $LR_e(i)$ for each year i of the time horizon can be defined, respectively, and are used in section 5.2 in the optimization process.

4.1.1 Illustration with the Irish condition scoring system

The evaluation and the condition rating in the EIRSPAN system is carried out for each component, taking into consideration the degree of distress or deterioration of the component and its ability to fulfil its function. The fault tree used to switch from a component level to a system level is illustrated in Figs. 6(a) and 6(b) for bridges (for failure modes 1 and 2, respectively). For such series system, the failure state is reached if a least one of the components fails. Loss of serviceability refers to a series system of bridge surface, expansion joints, and parapets/guardrails. Structural failure refers to a series system of abutments, piers, bearings, deck/slab and beams/girders/transverse beams.

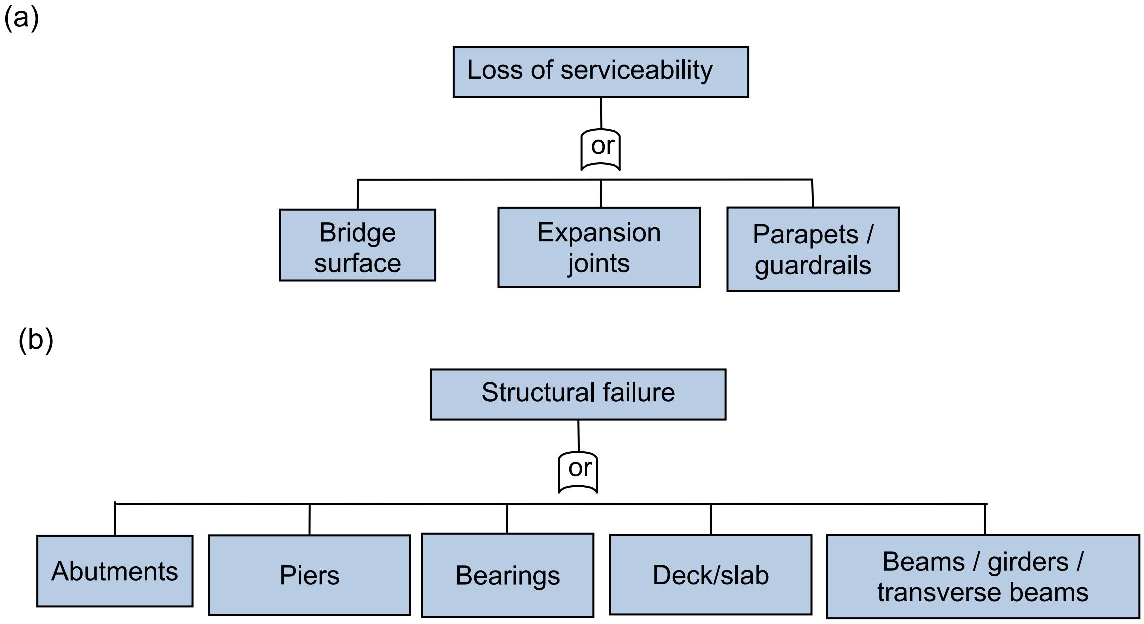


Figure 6. Fault tree model used for bridges (Irish case study) for (a) loss of serviceability and (b) structural failure.

Applying the optimization framework presented in Equation 2, the pure degradation transition matrices obtained on a sample of the EIRSPAN database are provided in Equations 5a-n. The degradation matrices $\boldsymbol{P_e}$ and $\boldsymbol{P_s}$ are shown in Equation 6. The probability of failure is then associated with the probability to be in the worst condition class (both for non structural and structural component systems).

Bridge surface

$$\begin{pmatrix} 0.90 & 0.09 & 0 & 0.01 & 0 & 0 \\ 0 & 0.67 & 0.33 & 0 & 0 & 0 \\ 0 & 0 & 0.92 & 0.08 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5a)$$

Piers

$$\begin{pmatrix} 0.89 & 0.11 & 0 & 0 & 0 & 0 \\ 0 & 0.73 & 0.27 & 0 & 0 & 0 \\ 0 & 0 & 0.51 & 0.49 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5b)$$

Expansion joints

$$\begin{pmatrix} 0.80 & 0.20 & 0 & 0 & 0 & 0 \\ 0 & 0.45 & 0.26 & 0.29 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5c)$$

Bearings

$$\begin{pmatrix} 0.84 & 0.15 & 0.01 & 0 & 0 & 0 \\ 0 & 0.81 & 0.19 & 0 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5d)$$

Footways/median

$$\begin{pmatrix} 0.80 & 0.17 & 0.03 & 0 & 0 & 0 \\ 0 & 0.84 & 0.15 & 0.01 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5e)$$

Deck/slab

$$\begin{pmatrix} 0.94 & 0.05 & 0.01 & 0 & 0 & 0 \\ 0 & 0.79 & 0.21 & 0 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5f)$$

Parapets/guardrails

$$\begin{pmatrix} 0.89 & 0.09 & 0 & 0.01 & 0 & 0 \\ 0 & 0.70 & 0.30 & 0 & 0 & 0 \\ 0 & 0 & 0.90 & 0.05 & 0.04 & 0.01 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5g)$$

Beams/girders/transverse beams

$$\begin{pmatrix} 0.83 & 0.16 & 0 & 0.01 & 0 & 0 \\ 0 & 0.78 & 0.22 & 0 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5h)$$

Embankments/slopes

$$\begin{pmatrix} 0.87 & 0.13 & 0 & 0 & 0 & 0 \\ 0 & 0.86 & 0.12 & 0.02 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5i)$$

Riverbed

$$\begin{pmatrix} 0.78 & 0.19 & 0.03 & 0 & 0 & 0 \\ 0 & 0.99 & 0.01 & 0 & 0 & 0 \\ 0 & 0 & 0.92 & 0.08 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5j)$$

Wing walls/retaining walls

$$\begin{pmatrix} 0.97 & 0.01 & 0.02 & 0 & 0 & 0 \\ 0 & 0.88 & 0.10 & 0.02 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5k)$$

Other elements

$$\begin{pmatrix} 0.60 & 0.39 & 0 & 0 & 0.01 & 0 \\ 0 & 0.82 & 0.17 & 0.01 & 0 & 0 \\ 0 & 0 & 0.75 & 0.25 & 0 & 0 \\ 0 & 0 & 0 & 0.94 & 0.06 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5l)$$

Abutments

$$\begin{pmatrix} 0.88 & 0.12 & 0 & 0 & 0 & 0 \\ 0 & 0.84 & 0.15 & 0.01 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5m)$$

Structure in general

$$\begin{pmatrix} 0.88 & 0.10 & 0.02 & 0 & 0 & 0 \\ 0 & 0.69 & 0.25 & 0.06 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5n)$$

$$\boldsymbol{P_e} = \begin{pmatrix} 0.73 & 0.27 & 0 & 0 & 0 & 0 \\ 0 & 0.71 & 0.23 & 0.06 & 0 & 0 \\ 0 & 0 & 0.75 & 0.16 & 0.07 & 0.02 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad \boldsymbol{P_s} = \begin{pmatrix} 0.80 & 0.20 & 0 & 0 & 0 & 0 \\ 0 & 0.72 & 0.22 & 0.06 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (6)$$

The comparison between data categorization and predictions made using the transition matrices $\boldsymbol{P_e}$ and $\boldsymbol{P_s}$ is shown in Figs. 7 and 8, respectively.

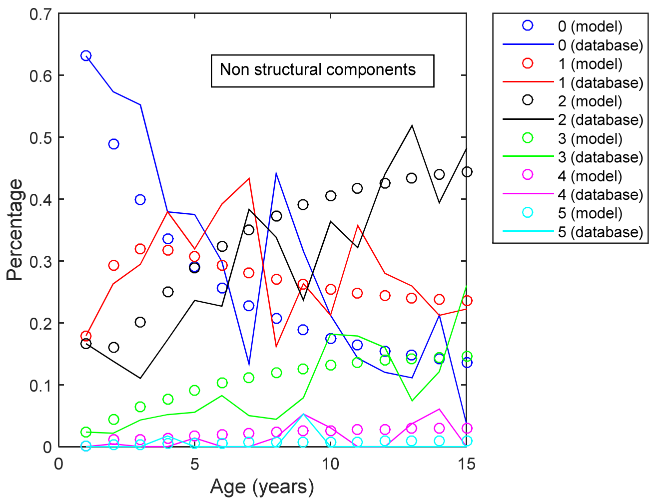


Figure 7. Profiles of condition score for non structural components (loss of serviceability)

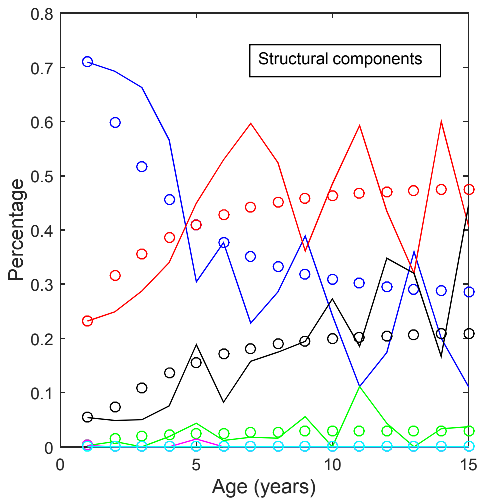


Figure 8. Profiles of condition scores for structural components (structural failure).

4.1.2 Illustration with the Danish condition scoring system

The fault tree used herein to switch from a component level to a system level is illustrated in Figs. 9(a) and 9(b) for bridges (for failure modes 1 and 2, respectively). For such series system, the failure state is reached if a least one of the components fails. A loss of serviceability refers to a series system of waterproofing, safety barriers/railings, expansion joints and drainage structure. Structural failure refers to a series system of bearings, and superstructure.

Applying the optimization framework presented in Equation 2, the pure degradation transition matrices obtained on a sample of the danish database are provided in Equations 7a-o. The degradation matrices $\boldsymbol{P_e}$ and $\boldsymbol{P_s}$ are shown in Equation 8. The probability of failure is then associated with the probability to be in the worst condition class (both for non structural and structural component systems).

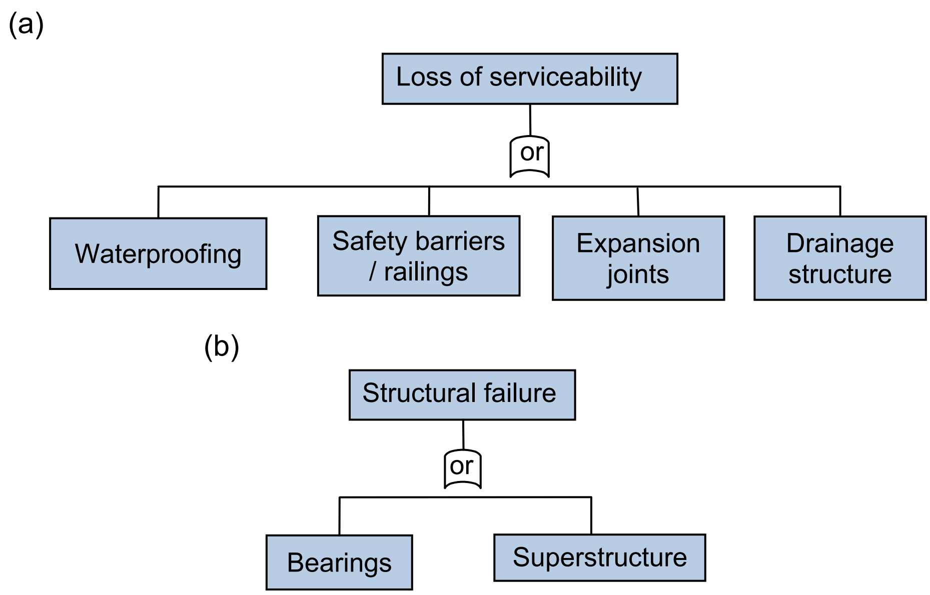


Figure 9. Fault tree model used for bridges (Danish case study) for (a) loss of serviceability and (b) structural failure.

Entire structure

$$\begin{pmatrix} 0.91 & 0.09 & 0 & 0 & 0 & 0 \\ 0 & 0.96 & 0.03 & 0 & 0.01 & 0 \\ 0 & 0 & 0.96 & 0.04 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7a)$$

Edge beams

$$\begin{pmatrix} 0.97 & 0.03 & 0 & 0 & 0 & 0 \\ 0 & 0.91 & 0.06 & 0.03 & 0 & 0 \\ 0 & 0 & 0.94 & 0.06 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7b)$$

Wings

$$\begin{pmatrix} 0.91 & 0.09 & 0 & 0 & 0 & 0 \\ 0 & 0.78 & 0.20 & 0.02 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7c)$$

Safety barriers/railings

$$\begin{pmatrix} 0.95 & 0.05 & 0.01 & 0 & 0 & 0 \\ 0 & 0.84 & 0.16 & 0 & 0 & 0 \\ 0 & 0 & 0.88 & 0.11 & 0.01 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7d)$$

Slopes

$$\begin{pmatrix} 0.95 & 0.04 & 0.01 & 0 & 0 & 0 \\ 0 & 0.90 & 0.09 & 0.01 & 0 & 0 \\ 0 & 0 & 0.93 & 0.07 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7e)$$

Pavement/surfacing

$$\begin{pmatrix} 0.91 & 0.09 & 0 & 0 & 0 & 0 \\ 0 & 0.84 & 0.16 & 0 & 0 & 0 \\ 0 & 0 & 0.86 & 0.14 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7f)$$

End support

$$\begin{pmatrix} 0.97 & 0.03 & 0 & 0 & 0 & 0 \\ 0 & 0.75 & 0.22 & 0.03 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7g)$$

Expansion joints

$$\begin{pmatrix} 0.86 & 0.13 & 0.01 & 0 & 0 & 0 \\ 0 & 0.54 & 0.25 & 0.17 & 0.04 & 0 \\ 0 & 0 & 0.43 & 0.57 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7h)$$

Intermediate support

$$\begin{pmatrix} 0.97 & 0.03 & 0 & 0 & 0 & 0 \\ 0 & 0.85 & 0.12 & 0.03 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7i)$$

Drainage structures

$$\begin{pmatrix} 0.92 & 0.06 & 0.01 & 0.01 & 0 & 0 \\ 0 & 0.61 & 0.28 & 0.08 & 0.03 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7j)$$

Bearings

$$\begin{pmatrix} 0.98 & 0.01 & 0.01 & 0 & 0 & 0 \\ 0 & 0.88 & 0.10 & 0.02 & 0 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7k)$$

Cross passage

$$\begin{pmatrix} 0.94 & 0.05 & 0.01 & 0 & 0 & 0 \\ 0 & 0.76 & 0.21 & 0.03 & 0 & 0 \\ 0 & 0 & 0.98 & 0.01 & 0.01 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7l)$$

Superstructure

$$\begin{pmatrix} 0.97 & 0.03 & 0 & 0 & 0 & 0 \\ 0 & 0.89 & 0.10 & 0.01 & 0 & 0 \\ 0 & 0 & 0.89 & 0.10 & 0.01 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7m)$$

Other elements

$$\begin{pmatrix} 0.75 & 0.23 & 0.02 & 0 & 0 & 0 \\ 0 & 0.65 & 0.23 & 0.11 & 0.01 & 0 \\ 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7n)$$

Waterproofing

$$\begin{pmatrix} 0.99 & 0.01 & 0 & 0 & 0 & 0 \\ 0 & 0.82 & 0.14 & 0.04 & 0 & 0 \\ 0 & 0 & 0.84 & 0.16 & 0 & 0 \\ 0 & 0 & 0 & 0.93 & 0.07 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (7o)$$

$$\boldsymbol{P_e} = \begin{pmatrix} 0.93 & 0.07 & 0 & 0 & 0 & 0 \\ 0 & 0.89 & 0.10 & 0 & 0.01 & 0 \\ 0 & 0 & 0.74 & 0.23 & 0.03 & 0 \\ 0 & 0 & 0 & 0.98 & 0.02 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad \boldsymbol{P_s} = \begin{pmatrix} 0.98 & 0.02 & 0 & 0 & 0 & 0 \\ 0 & 0.91 & 0.07 & 0.01 & 0.01 & 0 \\ 0 & 0 & 0.90 & 0.10 & 0 & 0 \\ 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (8)$$

Finally, the comparison between data categorization with predictions made using the transition matrices $\boldsymbol{P_e}$ and $\boldsymbol{P_s}$ is shown in Figs. 10 and 11, respectively.

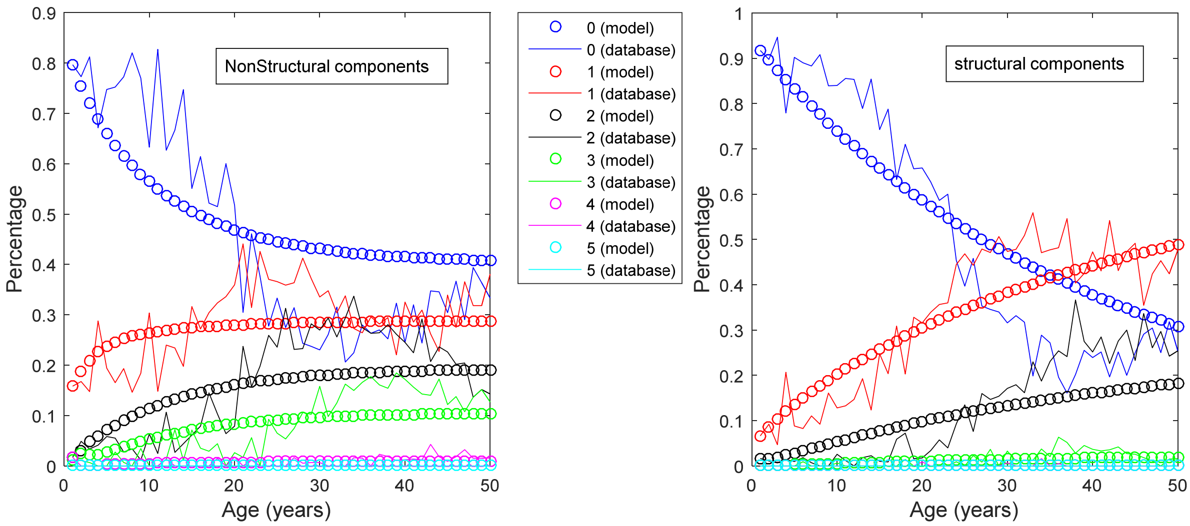


Figure 10. Profiles of condition score for equipment components

Figure 11. Profiles of condition scores for structural components

4.1.3 Illustration with the French condition scoring system

In the particular case of the French condition scoring system of bridges (French national road network managed by the French Ministry of Transportation, IQOA 2012a,b) , several components are visited such as bridge deck, expansion joints, waterproofing layer, bearings, and equipment. 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, equipment, and 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. 12(a) and 12(b) for bridges (for failure modes 1 and 2, respectively) and in Figs. 13(a) and 13(b) for walls (for failure modes 1 and 2, respectively). For such series systems, the failure state is reached if at least one of the components fails. For bridges, a loss of serviceability refers to a series system of expansion joints, waterproofing, and other equipment. A structural failure refers to a series system of bridge deck and bearings. For walls, a loss of serviceability refers to a series system of sewerage/drainage and equipment. Likewise, a structural failure refers to a series system of the zone of influence and structural condition.

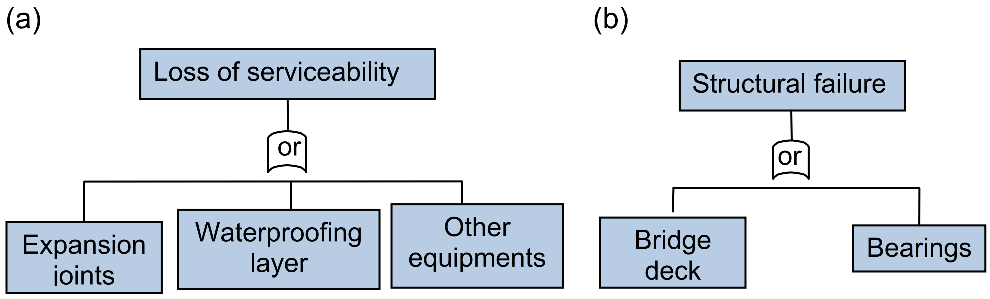


Figure 12. Fault tree model used for bridges (French case study) (a) loss of serviceability and (b) structural failure.

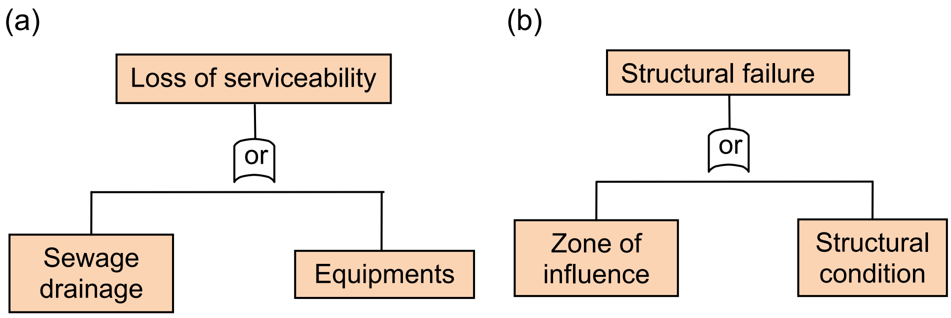
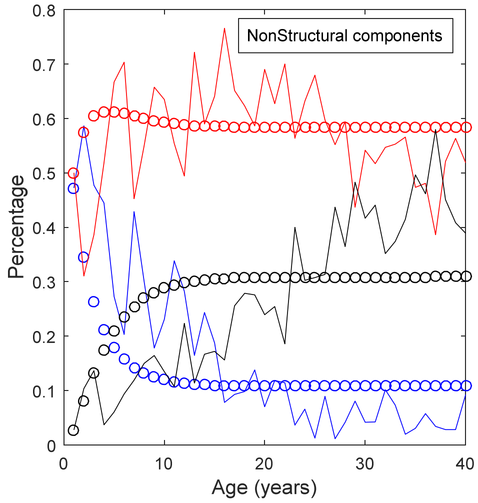


Figure 13. Fault tree model used for walls (French case study) for (a) loss of serviceability and (b) structural failure.

Applying the optimization framework presented in Equation 2, the pure degradation transition matrices $\boldsymbol{P}_e$ and $\boldsymbol{P}_s$ are shown in Equation 9.

$$\boldsymbol{P}_e = \begin{pmatrix} 0.66 & 0.34 & 0 \\ 0 & 0.88 & 0.12 \\ 0 & 0 & 1 \end{pmatrix} \qquad \boldsymbol{P}_s = \begin{pmatrix} 0.78 & 0.22 & 0 & 0 & 0 \\ 0 & 0.80 & 0.19 & 0 & 0.01 \\ 0 & 0 & 0.79 & 0.19 & 0.02 \\ 0 & 0 & 0 & 0.80 & 0.20 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \qquad (9)$$

The comparison between data categorization with predictions made using the transition matrices $\boldsymbol{P}_e$ and $\boldsymbol{P}_s$ is shown in Figs. 14 and 15, respectively.



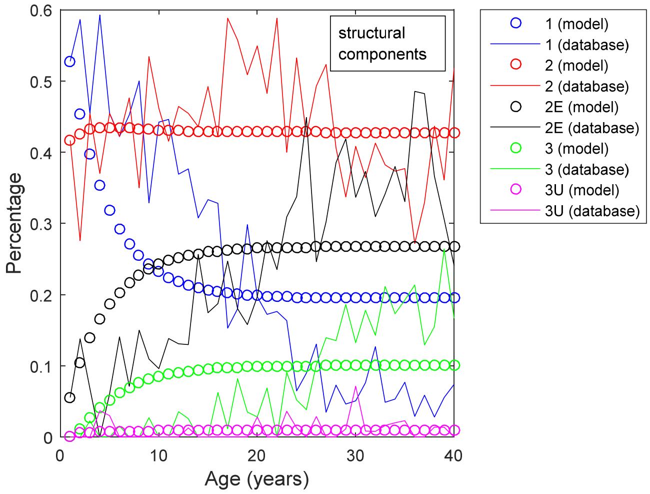


Figure 14. Profiles of condition score for structural components

Figure 15. Profiles of condition scores for equipment components.

As the predictions of the model and the trends in the database do not perfectly match, the second approach introduced in section 3.2.2 is used instead. 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 6 and 7 give an example on how new annual transition sequences can be built from the existing database.

Table 6. 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 7. 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 matrices associated with equipment and structural components, the new sequences identified with the approach exemplified in Tables 6 and 7 are used (and not the initial database anymore). An example of matrix developed based on a sample of the database of prestressed concrete bridges is provided in Equation 10.

$$\boldsymbol{P_s} = \begin{pmatrix} 0.74 & 0.19 & 0.06 & 0.01 & 0 \\ 0 & 0.89 & 0.10 & 0.01 & 0 \\ 0 & 0 & 0.91 & 0.09 & 0 \\ 0 & 0 & 0 & 0.94 & 0.06 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \qquad \boldsymbol{P_e} = \begin{pmatrix} 0.80 & 0.17 & 0.03 \\ 0 & 0.88 & 0.12 \\ 0 & 0 & 1 \end{pmatrix} \qquad (10)$$

The probability of failure is 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).

4.2 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 affected by each extreme event, and (ii) help assess the consequences associated with each impact on critical parts of the structure.

It is worth noting that these additional degradation matrices are not meant to model a change in the annual degradation rate (e.g., for carbonation) due to the temperature/CO2 concentration increase. Instead, they model the occurrence of a sudden event (storm, flood, heavy rains, etc.) that results from climate change for which we will control the frequency of occurrence and the percentage of the stock affected by this event.

Such matrices have to be in agreement with the scoring system used by NRAs. Considering the scoring systems in Ireland or Denmark with six condition states, the matrices CM_1 to CM_3 introduced in Equations 11a-c, respectively, are applied to a percentage of the infrastructure asset and with a certain frequency (depending on optimistic or pessimistic scenarios of climate change) in addition to the annual degradation matrices exemplified in Equation 6 (Irish case) or 8 (Danish case). A similar philosophy is applied in Equations 11d-f for additional transition matrices CM_1^* to CM_3^* applied to the series equipment system. Considering the scoring system in France with five states for structural components (1, 2, 2E, 3 and 3U) and three states for equipment components (1, 2 and 2E), the matrices CM_1 to CM_3 will be those provided in Equations 11g-i and the matrices CM_1^* to CM_3^* those provided in Equations 11j-l.

$$CM_1 = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (11a) \qquad CM_1 = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (11g)$$

$$CM_2 = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (11b) \qquad CM_2 = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (11h)$$

$$CM_3 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (11c) \qquad CM_3 = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (11i)$$

$$CM_1^* = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (11d) \qquad CM_1^* = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (11j)$$

$$CM_2^* = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (11e) \qquad CM_2^* = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix} \quad (11k)$$

$$CM_3^* = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (11f) \qquad CM_3^* = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix} \quad (11l)$$

Then, $x_{CM_i} CM_i P_s$ (or $x_{CM_i^*} CM_i^* P_e$) is applied every τ_i (or τ_i^*) on series structure system (or series equipment system). x_{CM_i} and $x_{CM_i^*}$ represent intensity coefficients in the sense that they stand for a percentage of the asset submitted to exceptional events, while τ_i and τ_i^* represent the frequency of the corresponding exceptional events. CM_1 is a "low scenario" which exacerbates equipment defects but without any impact on the structure (e.g., heavy wind). CM_2 is a medium scenario in which the condition score is systematically shifted by one score, even for structural condition (e.g., sea level rise, medium floods). Similarly CM_3 is a “severe” scenario with a sudden deterioration in the worst score (e.g., disastrous floods, landslide for walls).

Intensity coefficients and frequency of the events can be associated with each matrix in Equation 11 to characterize optimistic to pessimistic scenarios. Tables 8, 9 and 10 illustrate possible choices (according to the feedback of experts involved in the working group 2 of the RE-GEN project) among additional degradation matrices for bridge components, retaining walls and slopes, respectively.

Table 8. Additional degradation matrices associated with extreme events for bridge components.

Challenges	Impact	Expansion joints	Deck	Bearings	Water-proofing layer	Piers/ abutments	Equipment
Flooding and erosion	Flooding has the biggest impact on abutments/piers in case of scours	N/A	N/A	N/A	N/A (deck)	CM2 CM3	CM1 CM2
Landslides and avalanches	Landslides have the biggest impact on abutments/piers	CM1	CM2	CM2	N/A	CM3	CM2
Droughts	Deterioration of concrete elements	CM1 CM2	CM2	N/A	CM1 CM2	CM2	CM1
Sea Level Rise	Deterioration of concrete elements	N/A	CM1	CM1	CM2 (piers) N/A (deck)	CM1	CM1
Snowfall	Biggest impact is at deck and deck waterproofing	CM1	CM2	N/A	CM2	CM1	CM1 CM2
Windstorm	Highest impact set on the equipment	N/A	N/A	N/A	N/A	CM2 (in case of windstorm related wave impacts)	CM1 CM2

Table 9. Additional degradation matrices associated with extreme events for retaining walls components.

Challenges	Impact	Drainage	Structure	Zone of influence (backfill)
Flooding and erosion	Overall stability	CM2	CM2	CM3
Landslides and avalanches	Overall stability	CM2	CM2 CM3	CM2 CM3
Droughts	Concrete deterioration and global stability	N/A	CM2	CM2
Sea Level Rise	Structural deterioration	N/A	CM2	N/A
Snowfall	Overall stability	CM2	CM2 CM3	CM2 CM3
Windstorm	Vegetation on Backfill	CM1	CM2 CM3 (seaside) CM1 (other locations)	CM2 CM3

Table 10. Additional degradation matrices associated with extreme events for slopes.

Challenges	Impact	Drainage	Slope Body	Vegetation, erosion protection and other mitigation equipment
Flooding and erosion	Slope stability	CM2	CM2 CM3	CM2
Landslides and avalanches	Slope stability	CM2 CM3	CM2 CM3	CM2 CM3
Droughts	Slope stability	CM1	CM2	CM3
Sea Level Rise	Slope stability	CM1 CM2	CM2	CM2
Snowfall	Slope stability	CM2	CM2 CM3	CM2
Windstorm	Vegetation	CM1	CM 2 CM3 (seaside) CM2 (mountainous areas) CM1 (other areas)	CM1 CM2

4.3 Introduction of increase of traffic loads into the scoring system

For traffic increase, it is expected that the initial degradation matrix is slightly transformed by increasing the terms of degradation. This process will be performed for components most likely to suffer from traffic increase (e.g., bridge equipments).

Considering $\boldsymbol{P_e}$, the updated transition matrix $\tilde{\boldsymbol{P}}_e$ can be developed as follows:

$$\text{Irish case study: } \tilde{\boldsymbol{P}}_e = \begin{pmatrix} 0.73-\varepsilon & 0.27+\varepsilon & 0 & 0 & 0 & 0 \\ 0 & 0.71-\varepsilon & 0.23+\varepsilon & 0.06 & 0 & 0 \\ 0 & 0 & 0.75-\varepsilon & 0.16+\varepsilon & 0.07 & 0.02 \\ 0 & 0 & 0 & 0.99-\varepsilon & 0.01+\varepsilon & 0 \\ 0 & 0 & 0 & 0 & 0.99-\varepsilon & 0.01+\varepsilon \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (12a)$$

$$\text{Danish case study: } \tilde{\boldsymbol{P}}_e = \begin{pmatrix} 0.93-\varepsilon & 0.07+\varepsilon & 0 & 0 & 0 & 0 \\ 0 & 0.89-\varepsilon & 0.10+\varepsilon & 0 & 0.01 & 0 \\ 0 & 0 & 0.74-\varepsilon & 0.23+\varepsilon & 0.03 & 0 \\ 0 & 0 & 0 & 0.98-\varepsilon & 0.02+\varepsilon & 0 \\ 0 & 0 & 0 & 0 & 0.99-\varepsilon & 0.01+\varepsilon \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (12b)$$

$$\text{French case study: } \tilde{\boldsymbol{P}}_e = \begin{pmatrix} 0.80-\varepsilon & 0.17+\varepsilon & 0.03 \\ 0 & 0.88-\varepsilon & 0.12+\varepsilon \\ 0 & 0 & 1 \end{pmatrix} \quad (12c)$$

where $\varepsilon > 0$ and in such a way that (i) all terms are between 0 and 1, and (ii) the sum of all terms for each row equals 1 in matrix in 12a (or 12b or 12c).

5 Integration of risk analysis into asset management

The concepts introduced in the following are illustrated with the French case study. The approach is formulated in a general way so that it can be easily adapted to any condition scoring systems.

5.1 Maintenance strategies

Several prospective scenarios can be defined in the proposed framework. These scenarios can give priority either to preventive or corrective actions, 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 associated with the matrix $\boldsymbol{P_s}$ for the series structural system and with matrix $\boldsymbol{P_e}$ for the series equipment system, respectively (see Equation 10). 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. In the case of the French case study, the transition matrices that enhance repair actions for structure and equipment are

$$\boldsymbol{S}_{2,s} = \begin{pmatrix} 0.74 & 0.19 & 0.06 & 0.01 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix} \boldsymbol{S}_{2,e} = \begin{pmatrix} 0.80 & 0.17 & 0.03 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \tag{13}$$

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

$$\boldsymbol{S}_{3,s} = \begin{pmatrix} 0.74 & 0.19 & 0.06 & 0.01 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix} \boldsymbol{S}_{2,e} = \begin{pmatrix} 0.80 & 0.17 & 0.03 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \tag{14}$$

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 5.2.

5.2 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 for bridge, walls, and 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 the work of 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 $\boldsymbol{X}^i_{S_j} = {}^t\left(x^i_{S_j,1} \quad x^i_{S_j,2} \quad x^i_{S_j,2E} \quad x^i_{S_j,3} \quad x^i_{S_j,3U}\right)$ is associated with the strategy S_j. The term $\boldsymbol{X}^i_{S_j}(k) = x^i_{S_j,k}$ represents the proportion of bridges scored k for which strategy 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

$$\boldsymbol{q}^{i+1} = \boldsymbol{q}^{i}\ \boldsymbol{M}_i \qquad \forall i = 1,\ldots,n-1, \tag{15}$$

where

$$\boldsymbol{M}_i = \sum_{j=1}^{m} \begin{pmatrix} x^{i}_{s_j,1} & & 0 \\ & \ddots & \\ 0 & & x^{i}_{s_j,3U} \end{pmatrix} \boldsymbol{S}_j \tag{16}$$

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

$$\sum_{j=1}^{m} x^{i}_{s_j,k} = 1 \qquad \forall i = 1,\ldots,n-1, \forall k \in \{1,2,2E,3,3U\} \tag{17}$$

In Equation 16, $\boldsymbol{S}_j$ can represent not only the various maintenance scenarios considered by the owner, but also the exceptional degradation matrices due to climate change (see Section 4.2). The fractions $x^{i}_{s_j,k}$ 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 $x^{i}_{s_j,k}$ associated with decisions of the owner will be the variables in the optimization process. They will be determined in such a way that the conditions of the bridge/retaining wall components remain above a minimal threshold while the costs are as low as possible. The constraint on $x^{i}_{s_j,k}$ ensures that, taking into account the fraction of bridges that are analyzed, the final matrix $\boldsymbol{M}_i$ verifies the property

$$\sum_{q=1}^{5} \boldsymbol{M}_i(p,q) = 1 \qquad \forall i = 1,\ldots,n-1, \forall p = 1,\ldots,5 \tag{18}$$

Each strategy $\boldsymbol{S}_j$ is associated with a cost vector $\boldsymbol{C}_{S_j} = {}^{t}\begin{pmatrix} c_{S_j,1} & c_{S_j,2} & c_{S_j,2E} & c_{S_j,3} & c_{S_j,3U} \end{pmatrix}$ where the *kth* element of $\boldsymbol{C}_{S_j}$ ($k \in \{1,2,2E,3,3U\}$) is:

$$\boldsymbol{C}_{S_j}(k) = \left\langle \begin{pmatrix} \delta_{1,k} & \delta_{2,k} & \delta_{2E,k} & \delta_{3,k} & \delta_{3U,k} \end{pmatrix} \boldsymbol{S}_j, \begin{pmatrix} \delta_{1,k} & \delta_{2,k} & \delta_{2E,k} & \delta_{3,k} & \delta_{3U,k} \end{pmatrix} \boldsymbol{C} \right\rangle \tag{19}$$

where $\boldsymbol{S}_j =$ *jth* strategy matrix ($j = 1$ or 2 herein), $\langle .,. \rangle =$ scalar product notation, and $\delta_{l,k} =$ Kronecker function ($\delta_{l,k} = 1$ if $l = k$, $\delta_{l,k} = 0$ if $l \neq k$). A strategy $\boldsymbol{S}_j$ is entirely defined by the associated transition matrix $\boldsymbol{S}_j$, as previously mentioned.
The annual cost for the structural series system is the sum of all the costs from the different strategies for each year i:

$$C_{a,s}(i) = A_T \sum_{j=1}^{m} \sum_{k \in K} \boldsymbol{X}^{i}_{S_j}(k) \boldsymbol{C}_{S_j}(k)\, q^{i}_{k} \tag{20}$$

where $K = \{1,2,2E,3,3U\}$, $\boldsymbol{X}^{i}_{S_j}(k) =$ fraction of bridges with score k concerned by strategy $\boldsymbol{S}_j$ at year i, $\boldsymbol{C}_{S_j}(k) =$ cost of the strategy $\boldsymbol{S}_j$ for bridge/retaining wall component scored k, and $q^{i}_{k} =$ percentage of the component scored k at year i.

A procedure similar to that described in Equations 15-20 enables to calculate the annual cost $C_{a,e}(i)$ for the equipment series system.

Several optimization scenarios are possible and two are detailed thereafter.
The first one, detailed in Equations 21(a-c) is aimed at minimizing $C_a(i)$ every year i of the planning:

$$\text{Find } x_{s_j}^{i} \qquad \forall j = 1 \ldots m,\ \forall i = 1 \ldots n-1 \tag{21a}$$

$$\text{to} \qquad \text{Minimize } \frac{\alpha_i\left(C_{a,s}(i)+C_{a,e}(i)\right)+\left[1-\alpha_i\right]\left(LR_s(i)+LR_e(i)\right)}{(1+r)^i} \qquad \forall i = 1 \ldots n-1 \tag{21b}$$

$$\text{such that} \qquad LP > LP_0 \qquad \forall i = 1 \ldots n \tag{21c}$$

where $r =$ yearly discount rate of money fixed at 2% in all calculation illustrated in this report; α_i is a parameter between 0 and 1 that controls the willingness to take into account the risk in the minimization problem. 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. For such an optimization problem, several algorithms can be used among which the interior-point optimization (Byrd et al. 1999, 2000, Waltz 2006), the SQP optimization (Powel 1978a,b), the active-set optimization (Powel 1978a,b), of the trust-region-reflective optimization (Coleman et al. 1994, 1996).

The second one, detailed in Equations 22(a-d), is aimed at minimizing simultaneously the total maintenance cost and the risk cumulated during the overall planning horizon:

$$\text{Find } x_{s_j}^{i} \qquad \forall j = 1 \ldots m,\ \forall i = 1 \ldots n-1 \tag{22a}$$

$$\text{to} \qquad \text{Minimize } \sum_{i=1}^{n-1}\left(\frac{C_{a,s}(i)+C_{a,e}(i)}{(1+r)^i}\right) \tag{22b}$$

$$\text{and} \qquad \text{Minimize } \sum_{i=1}^{n-1}\left(\frac{LR_s(i)+LR_e(i)}{(1+r)^i}\right) \tag{22c}$$

$$\text{such that} \qquad LP > LP_0 \qquad \forall i = 1 \ldots n \tag{22d}$$

Several methods exist to solve the optimization problem in Equation 22. 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 trade-off among available financial resources, necessary safety and condition levels, and acceptable levels of structural deterioration.

6 Optimization results

As mentioned in Section 5, the concepts introduced herein are illustrated with the French case study. The approach is formulated in a general way so that it can be easily adapted to any condition scoring systems.

6.1 Mono-objective optimization

In this section, the optimization framework considered in Equation 21 is chosen by considering several cases. The main objective is to show how (i) considering risk, (ii) considering different levels of quality constraints, (iii) applying or not additional degradation due to climate change, and (iv) applying continuous additional degradation due to traffic growth can impact optimal maintenance and repair strategies. The optimization process described in Section 5 is applied to a sample of prestressed concrete bridges (total deck area of the stock is 1.8324×10^6 m^2) to determine the maintenance strategies for the next 30 years considering initial distributions $\boldsymbol{q}_s^0 = \begin{pmatrix} 0.07 & 0.41 & 0.35 & 0.15 & 0.02 \end{pmatrix}$ and $\boldsymbol{q}_e^0 = \begin{pmatrix} 0.06 & 0.53 & 0.41 \end{pmatrix}$ for structural and component series systems, respectively. Results include:

- evolution of condition for structural series system (subfigure a in Figs. 16 to 23),
- evolution of condition for component series system (subfigure b in Figs. 16 to 23),
- annual maintenance costs for structural series system (subfigure c in Figs. 16 to 23),
- annual maintenance costs for component series system (subfigure d in Figs. 16 to 23),
- total annual maintenance cost (subfigure e in Figs. 16 to 23).

To calculate the costs detailed in Equations 19 and 20, the following cost matrix is considered using some recent cost surveys in France and considering that the additional weighting factors 0.5 and 0.1 apply to structural and equipment components:

$$\boldsymbol{C} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 99.5 & 0 & 0 & 0 & 0 \\ 271 & 271\times 0.9 & 0 & 0 & 0 \\ 287 & 287\times 0.9 & 287\times 0.8 & 0 & 0 \\ 785 & 785\times 0.9 & 785\times 0.8 & 785\times 0.7 & 0 \end{pmatrix} \qquad (23)$$

6.1.1 Impact of considering risk in the optimization process

In this section, the mono-objective problem of Equation 21 is considered by applying $\alpha_i = 1$ and $\alpha_i = 0.7$ in Figs. 16 and 17, respectively. The constraint on LP is associated with the following set of constraints:

$$\begin{cases} \boldsymbol{q}_s^i(1) \geq \boldsymbol{q}_s^1(1) \\ \boldsymbol{q}_s^i(1)+\boldsymbol{q}_s^i(2) \geq \boldsymbol{q}_s^1(1)+\boldsymbol{q}_s^1(2) \\ \boldsymbol{q}_s^i(3) \leq \boldsymbol{q}_s^1(3) \\ \boldsymbol{q}_s^i(4)+\boldsymbol{q}_s^i(5) \leq \boldsymbol{q}_s^1(4)+\boldsymbol{q}_s^1(5) \\ \boldsymbol{q}_s^i(5) \leq \boldsymbol{q}_s^1(5) \end{cases} \text{and} \begin{cases} \boldsymbol{q}_e^i(1) \geq \boldsymbol{q}_e^1(1) \\ \boldsymbol{q}_e^i(1)+\boldsymbol{q}_e^i(2) \geq \boldsymbol{q}_e^1(1)+\boldsymbol{q}_e^1(2) \\ \boldsymbol{q}_e^i(3) \leq \boldsymbol{q}_e^1(3) \end{cases} \quad (24)$$

Considering risk-based cost when choosing $\alpha_i = 0.7$ dramatically changes the strategy concerning equipment components (Fig. 17b) and associated annual maintenance costs (Fig. 17d).

6.1.2 Impact of quality constraints in the optimization process

In this section, the mono-objective problem of Equation 21 is considered by applying $\alpha_i = 1$ and by considering quality constraints of Equation 24 (constraint scenario 1) and those of Equation 25 (constraint scenario 2) in Figs. 18 and 19. The constraint on LP is associated with the following set of constraints:

$$\begin{cases} \boldsymbol{q}_s^i(1) \geq \boldsymbol{q}_s^1(1) \\ \boldsymbol{q}_s^i(1)+\boldsymbol{q}_s^i(2) \geq 55\% \\ \boldsymbol{q}_s^i(3) \leq 30\% \\ \boldsymbol{q}_s^i(4)+\boldsymbol{q}_s^i(5) \leq 15\% \\ \boldsymbol{q}_s^i(5) \leq \boldsymbol{q}_s^1(5) - \dfrac{\boldsymbol{q}_s^1(5)-1\%}{30} i \end{cases} \text{and} \begin{cases} \boldsymbol{q}_e^i(1) \geq \boldsymbol{q}_e^1(1) \\ \boldsymbol{q}_e^i(1)+\boldsymbol{q}_e^i(2) \geq 55\% \\ \boldsymbol{q}_e^i(3) \leq 30\% \end{cases} \quad (25)$$

By comparing Figs. 18 and 19, it is shown that having higher quality constraints significantly influences the maintenance strategy in the first year (to ensure constraints are satisfied) while the maintenance cost/condition score is stable in subsequent years.

6.1.3 Impact of climate change in the optimization process

In this section, the mono-objective problem of Equation 21 is considered by applying $\alpha_i = 1$ and by considering quality constraints of Equation 25 (constraint scenario 2). In comparison with a scenario without additional degradation (Fig. 20), additional degradation matrices CM_2 and CM_3 are applied in Fig. 21 every 10 and 15 years on 5% and 1% of the bridge stock for structural components; also, CM_1^* and CM_2^* are applied every 5 and 10 years on 5% and 5% of the bridge stock for equipment components (Section 4.2). The need for additional efforts (from an economic perspective) can be determined by comparing Fig. 20c with Fig. 21c, Fig. 20d with Fig. 21d, and Fig. 20e with Fog. 21e.

6.1.4 Impact of traffic growth in the optimization process

In this section, the mono-objective problem of Equation 21 is considered by applying $\alpha_i = 1$ and by considering quality constraints of Equation 25 (constraint scenario 2). No additional degradation due to climate change is considered. Only additional impacts due to traffic growth are considered by fixing $\varepsilon = 0.03$ in Equation 12c (Fig. 23) and are compared with the case without additional degradation due to traffic growth (Fig. 22). It is shown that the annual maintenance cost associated with the equipment series system is slightly increased (by comparing Figs. 22d and 23d, and then Figs. 22e and 23e).

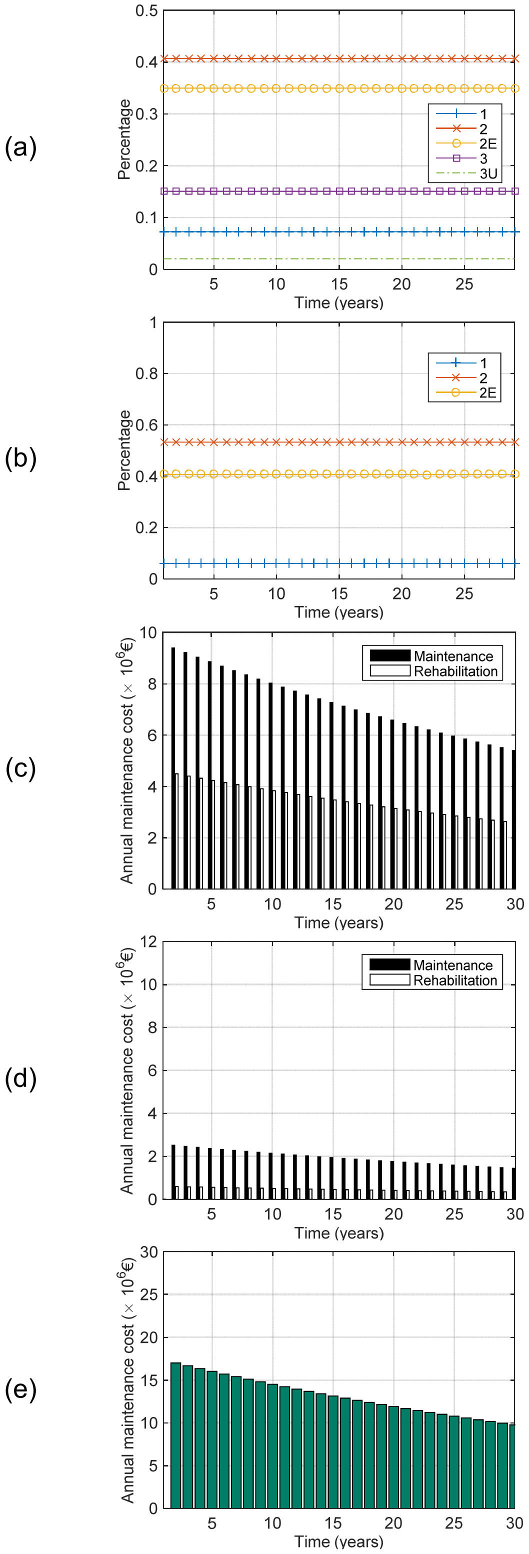


Figure 16. Results of the optimization process with α_i=1.

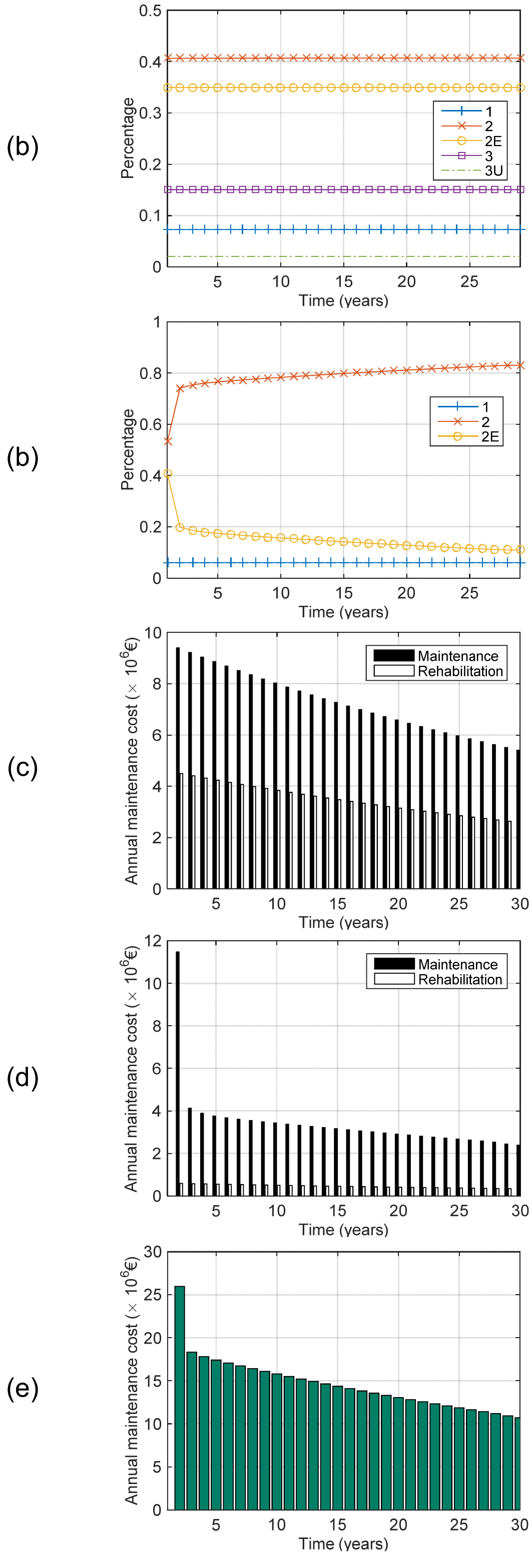


Figure 17. Results of the optimization process with α_i=0.7.

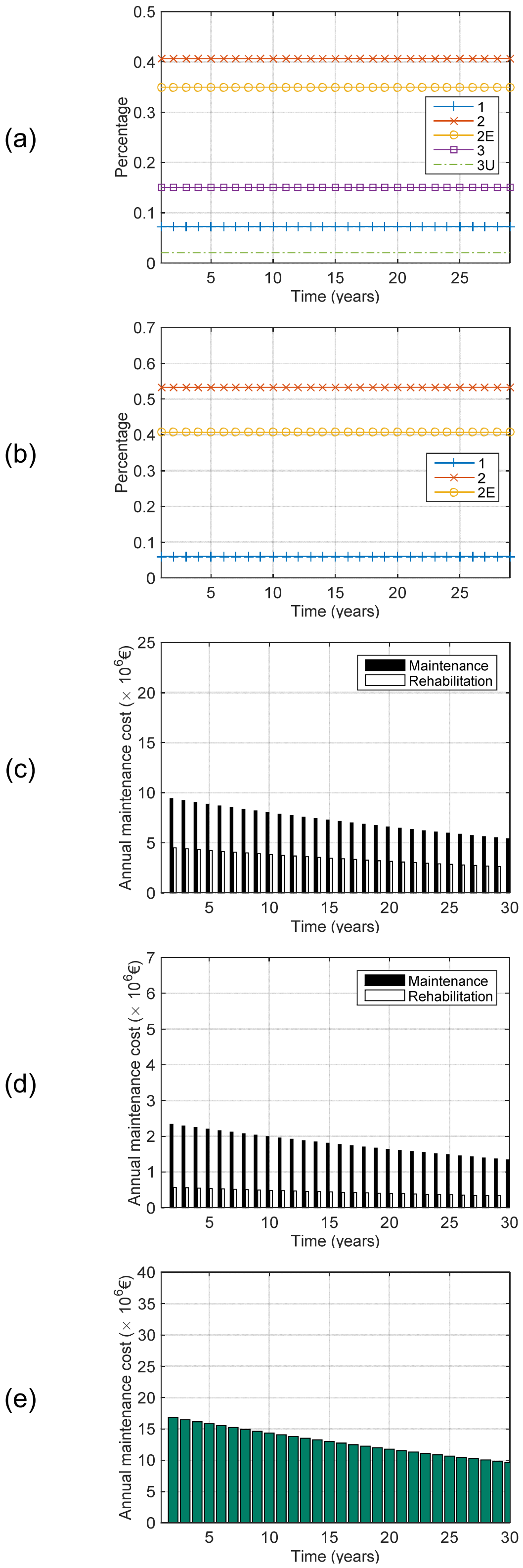


Figure 18. Results of the optimization process with constraint scenario 1.

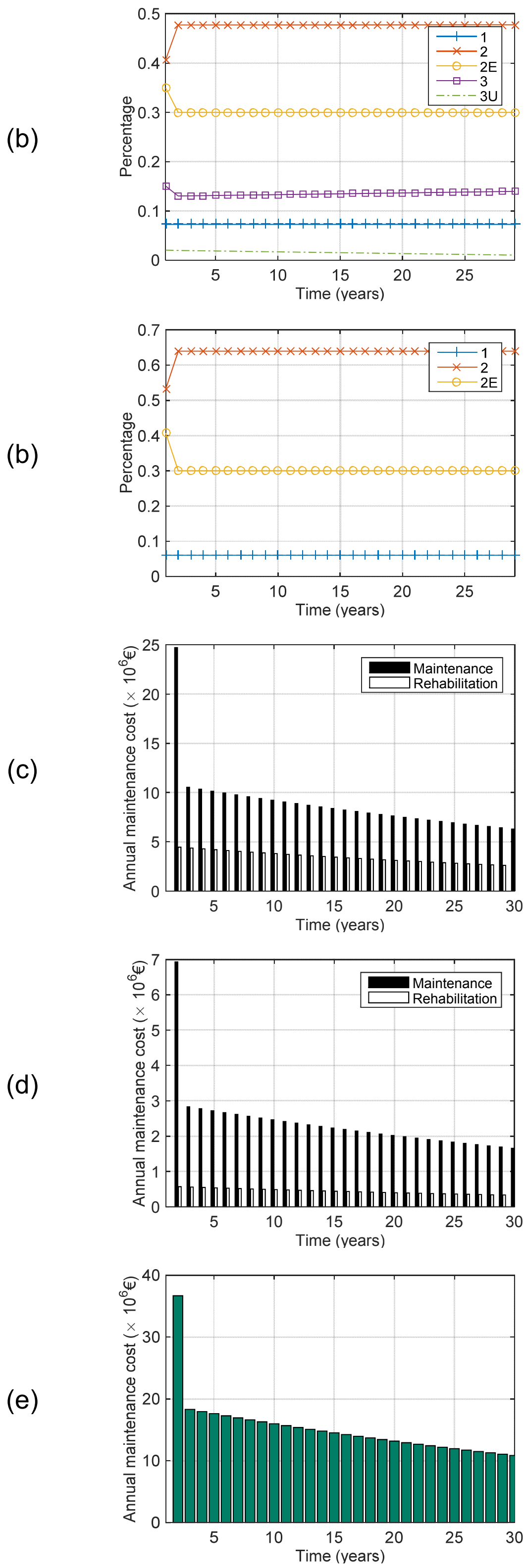


Figure 19. Results of the optimization process with constraint scenario 2.

(a) (b) (c) (d) (e)

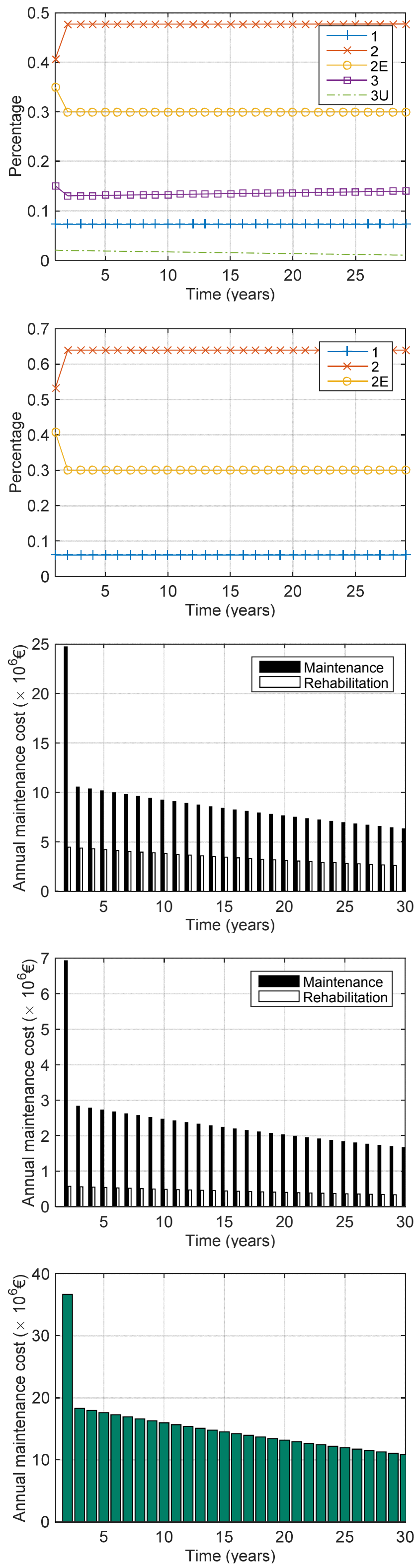


Figure 20. Results of the optimization process without additional degradation.

(b) (b) (c) (d) (e)

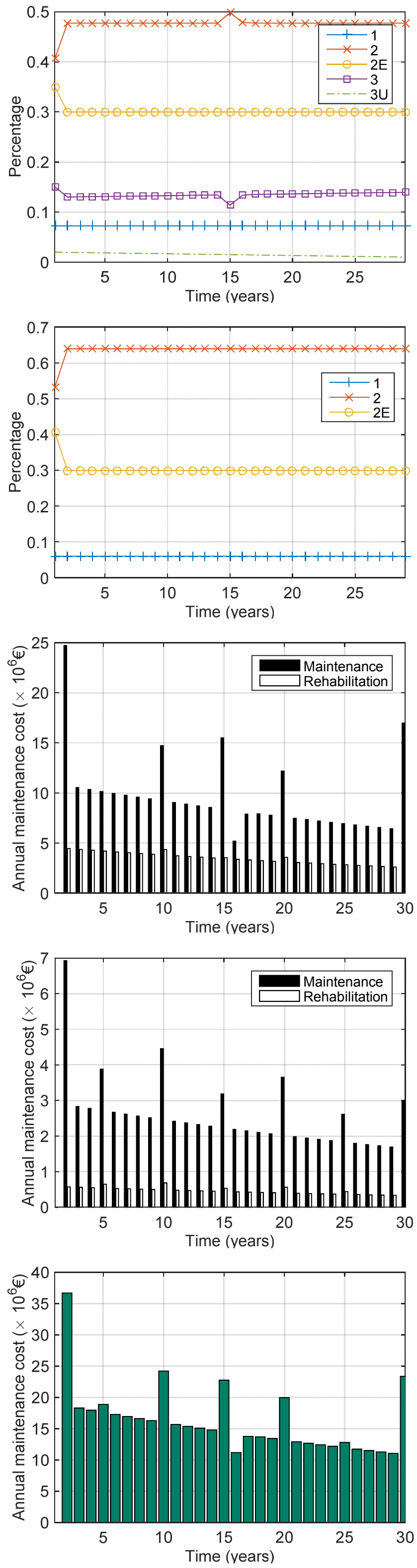


Figure 21. Results of the optimization process with additional degradation.

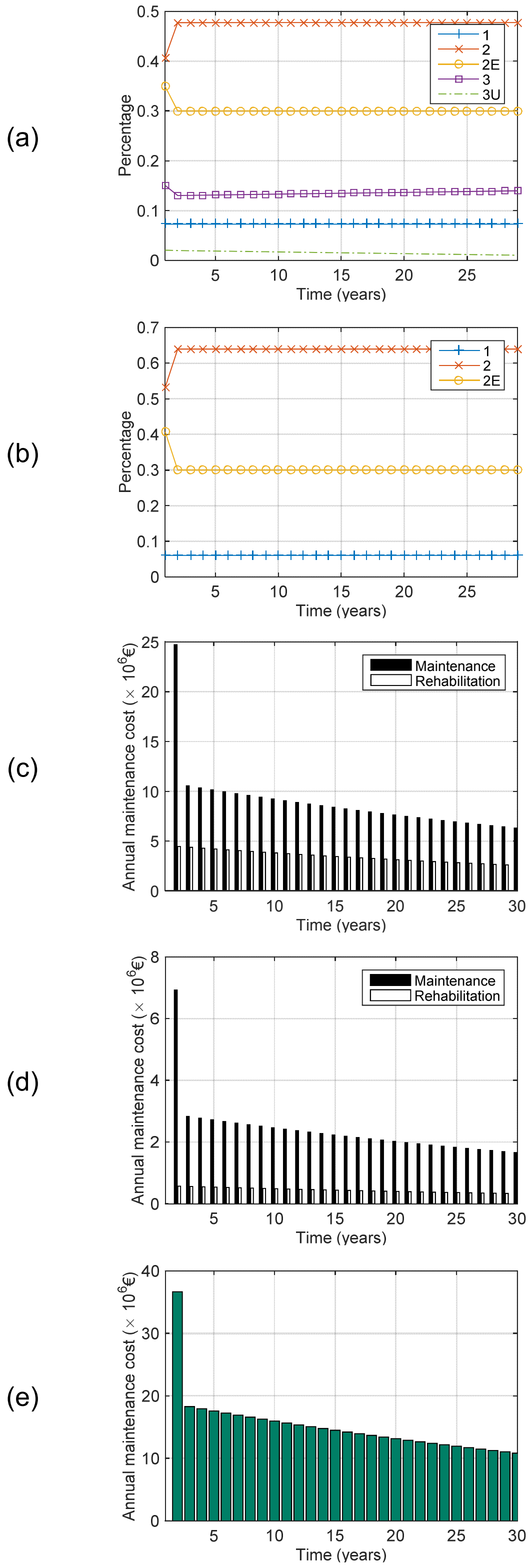


Figure 22. Results of the optimization process without additional effect of traffic growth.

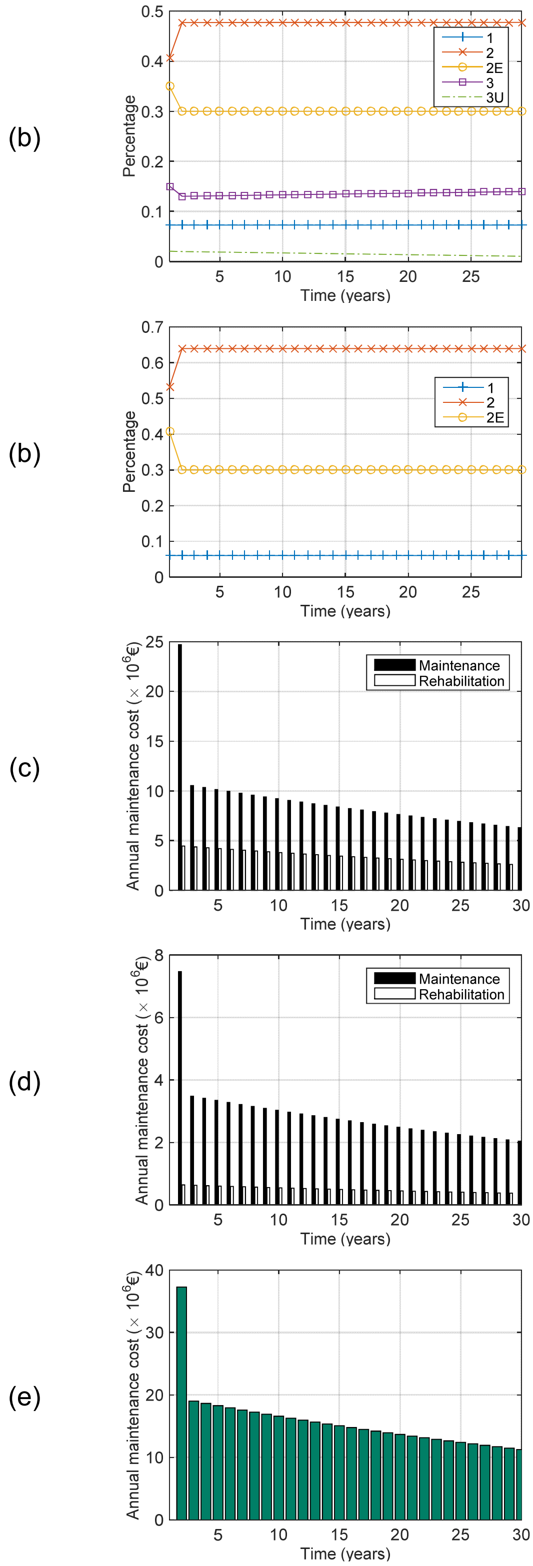


Figure 23. Results of the optimization process with additional effect of traffic growth ($\varepsilon = 0.03$ in Equation 12c).

6.2 Multi-objective optimization

Considering the bi-objective problem of Equation 22, an example of optimal Pareto solutions is shown in Fig. 24, for a time horizon of 30 years.
Three scenarios "optimistic", "mean", and "pessimistic" are considered in this figure for illustrative purposes. The performance constraints to be respected each year i over the n years of the time horizon are as follows: $\%1 > 55\%$, $\%2 + \%2E < 30\%$, $\%3 + \%3U < 15\%$ and $\%3U(i) < \%3U(0) - \frac{\%3U(0) - 1\%}{30} i$. The intensity and frequency coefficients are provided in Table 11. It can be seen from Fig. 24 that maintenance cost and risk increase with the intensities and the frequencies of extreme events which have a direct impact on the overall condition of the asset.

Table 11. Coefficients considered for intensity and frequency of extreme events (see section 4.2).

Coefficients	Optimistic	Mean	Pessimistic
x_{CM_1} ; τ_1	0 ; -	0 ; -	0 ; -
x_{CM_2} ; τ_2	0 ; -	5% ; 10 years	5% ; 7 years
x_{CM_3} ; τ_3	0 ; -	1% ; 15 years	1% ; 10 years
$x_{CM_1^*}$; τ_1^*	0 ; -	5% ; 7 years	5% ; 5 years
$x_{CM_2^*}$; τ_2^*	0 ; -	5% ; 10 years	5% ; 7 years

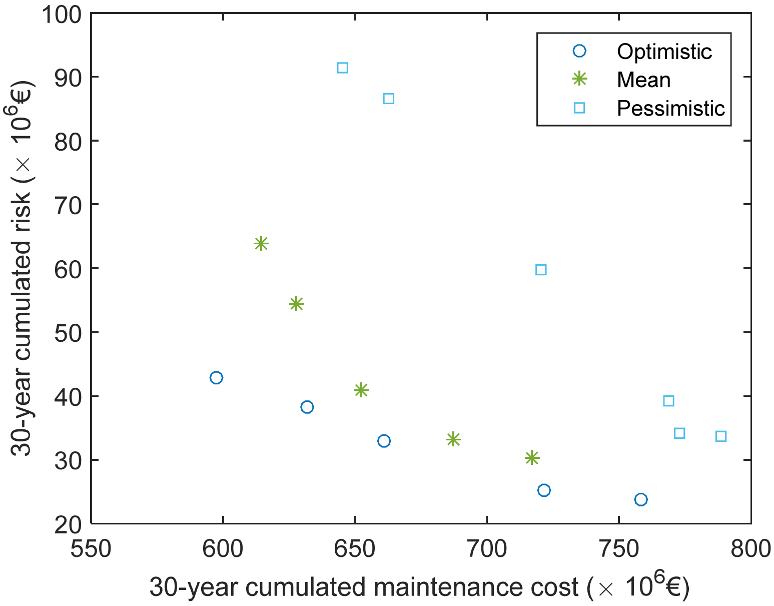


Figure 24. Pareto Fronts obtained with optimistic, mean and pessimistic scenarios (see Table 11).

6.3 Consideration of uncertainties in the optimization framework

In this section, uncertainties associated with some parameters are considered. The mono-objective problem of Equation 21 is considered by applying $\alpha_i = 1$ and subject to quality constraints of Equation 25 (constraint scenario 2), and is run 10000 times assuming a normal distribution for the parameters in Table 12 (with additional degradation due to climate change) and Table 13 (without additional degradation).

Table 12. Uncertainties on some parameters of the model (with additional degradation due to climate change).

Coefficients	Mean	COV
x_{CM_1} ; τ_1	3% ; 5 years	10%
x_{CM_2} ; τ_2	3% ; 10 years	10%
x_{CM_3} ; τ_3	1% ; 15 years	10%
$x_{CM_1^*}$; τ_1^*	3% ; 5 years	10%
$x_{CM_2^*}$; τ_2^*	3% ; 10 years	10%
$\boldsymbol{C}(2,1)$	99.5	10%
$\boldsymbol{C}(3,1)$	271	10%
$\boldsymbol{C}(4,1)$	287	10%
$\boldsymbol{C}(5,1)$	785	10%

Table 13. Uncertainties on some parameters of the model (without additional degradation due to climate change).

Coefficients	Mean	COV
x_{CM_1} ; τ_1	0% ; -	-
x_{CM_2} ; τ_2	0% ; -	-
x_{CM_3} ; τ_3	0% ; -	-
$x_{CM_1^*}$; τ_1^*	0% ; -	-
$x_{CM_2^*}$; τ_2^*	0% ; -	-
$\boldsymbol{C}(2,1)$	99.5	10%
$\boldsymbol{C}(3,1)$	271	10%
$\boldsymbol{C}(4,1)$	287	10%
$\boldsymbol{C}(5,1)$	785	10%

Optimization results are presented in the form of boxplots to show the impact of uncertainties in the model. A boxplot is a convenient way of graphically depicting groups of numerical data through their quartiles. The lines extending vertically from the boxes (whiskers) indicate variability outside the upper and lower quartiles. Outliers are not plotted in the following figures.

Fig. 25 represents the total annual maintenance cost for the next 30 years with and without including additional degradation due to climate change. It is highlighted how these additional effects may increase the costs, both in value and variability.

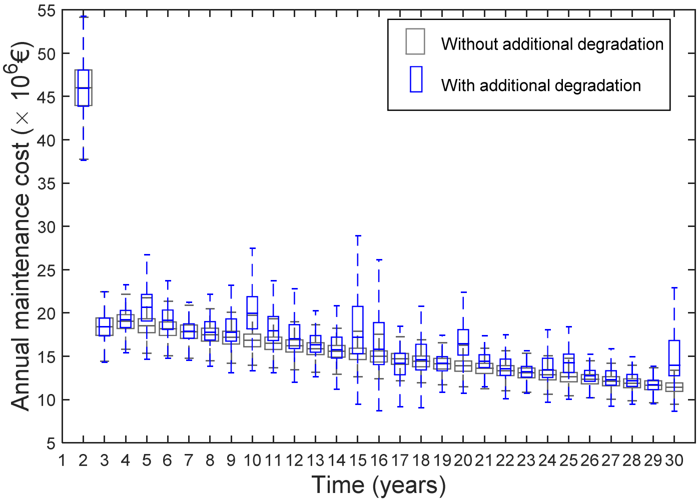


Figure 25. Overall annual maintenance cost without or with additional degradation due to climate change.

The annual maintenance costs for structural and equipment components are also detailed in Figs. 26 and 27, and similar effects can be observed in these figures as to how additional degradation affects both structural and equipment components.

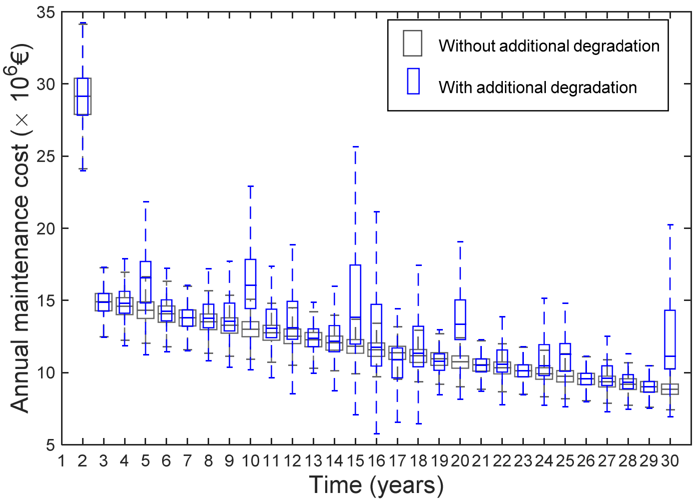


Figure 26. Annual maintenance cost for structural components without or with additional degradation due to climate change.

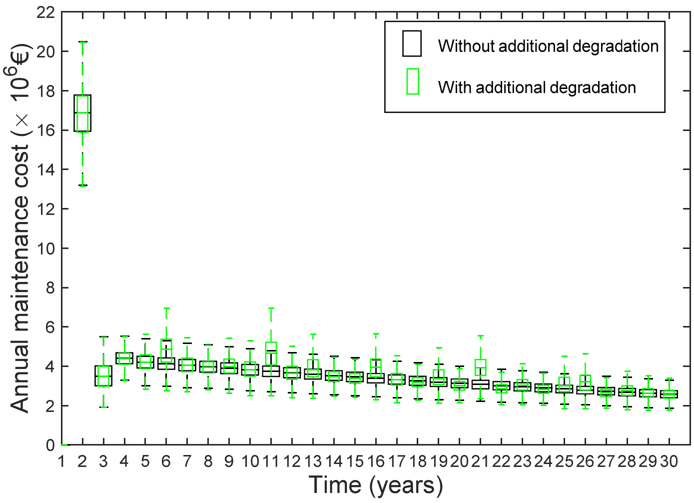


Figure 27. Annual maintenance cost for equipment components without or with additional degradation due to climate change.

Finally uncertainties associated with condition scores are shown in Figs. 28 and 29, for structural and equipment components, in each case with or without additional degradation. It is observed how additional degradation impacts structural/equipment components. Such an effect was already partially observed in the deterministic simulation shown in Fig. 21.

(a) (b)

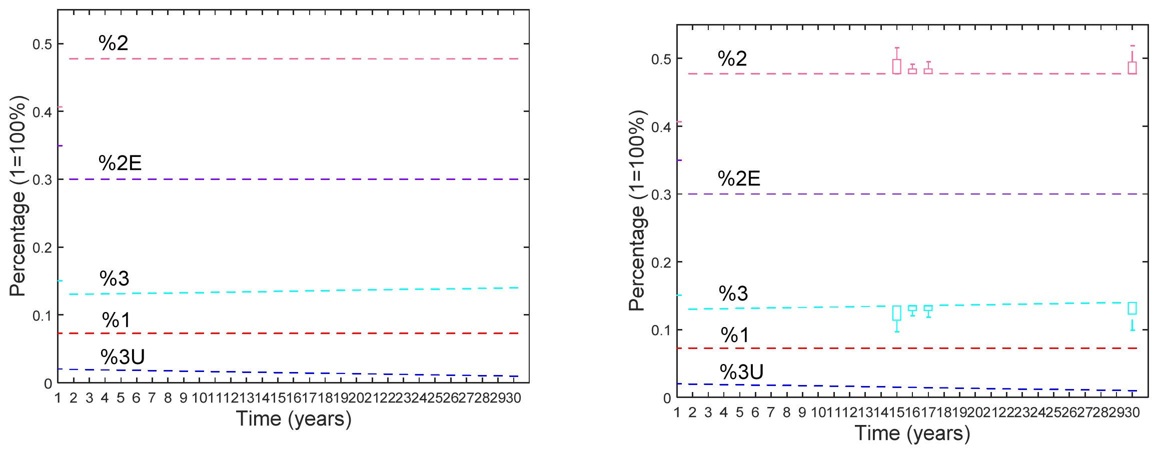
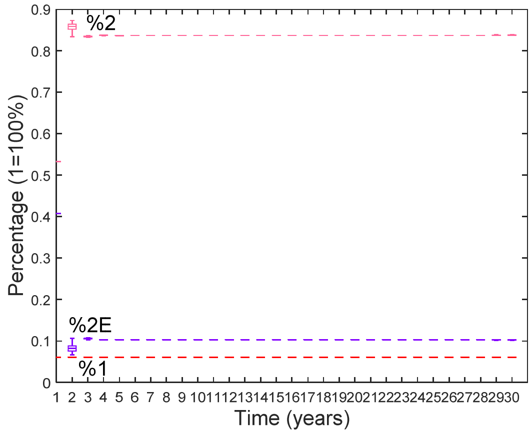


Figure 28. Percentage in each condition score for structural components (a) without and (b) with additional degradation due to climate change.

(a) (b)



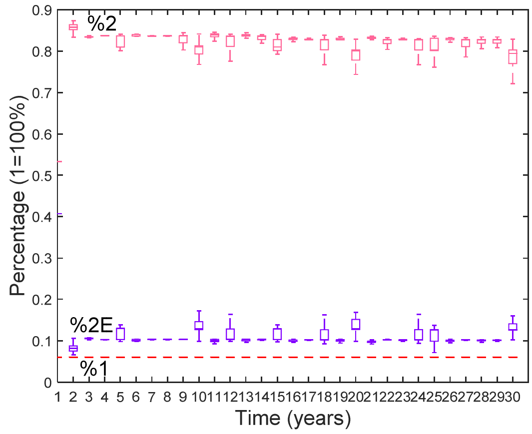


Figure 29. Percentage in each condition score for equipement components (a) without and (b) with additional degradation due to climate change.

7 Conclusions

Managing assets is about collecting information and making decisions. Due to the complexity of the decision-making process and the diversity of the assets to which allocate the funds, the asset management is seen as an ongoing and long-term effort.

Dealing with ageing infrastructures, increase of traffic demand, and climate change, several important questions arise for road assets. These relate to the determination of the lifecycle of a new, maintained, rehabilitated or retrofitted structure and its expected performance along the lifecycle.

The proposed optimization framework is based on visual inspections (e.g., condition rating) and enables to determine optimal asset management strategies for bridges, retaining walls and steep embankments considering the age of infrastructures, traffic volume, and environmental conditions.

Using as input the inventory of the asset and condition assessment, the proposed method aims to determine some degradation profiles for bridge components and retaining walls. Once the degradation profiles are determined, they are used to characterize how the degradation of infrastructures evolves with time. Different types of hazards are then considered (including the potential impact of climate change and traffic increase), and risk is defined as a joint measure of vulnerability and consequences of failure.

Optimal management strategies, based on the consequences of possible actions on the future condition of the system, are determined through an optimization process under uncertainty. The aim is to minimize the risk level while maximizing the performance level of structures. The optimization problem can be employed to minimize both one objective and multi-objective functions aiming at simultaneously minimizing several impacts. The effect of uncertainties on some parameters is also investigated. Such an optimization procedure can allow NRAs assessing the necessary additional effort to satisfy performance constraints under different scenarios of traffic changes and climate change.

It is noted that a risk analysis tool has been developed to apply the analysis to ageing infrastructures under alternative climate change and traffic growth scenarios. The proposed package runs in MATLAB programming environment and is designed to be easily used by end users in Europe.

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The opinions and conclusions presented in this report are those of the author and do not necessarily reflect the views of the sponsoring organizations.

9 References

AASHTO (1997a). 21st Century Asset Management. American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (2002). Transportation Asset Management Guide. American Association of State Highway and Transportation Officials, Washington, D.C.

Bazaraa, M.S., Sherali, H.D. and Shetty, C.M., Non Linear Programming: Theory and Algorithms, 1992 (Wiley).

BRIME (2001), Project funded by the European Commission under the Transport, RTD Programme of the 4th Framework Programme - Bridge Management and Condition Monitoring, BRIME PL97-2220, 2001.

Byrd, R.H., Mary E. Hribar, and Jorge Nocedal, (1999). "An Interior Point Algorithm for Large-Scale Nonlinear Programming," SIAM Journal on Optimization, Vol 9, No. 4, pp. 877–900.

Byrd, R. H., J. C. Gilbert, and J. Nocedal. (2000). "A Trust Region Method Based on Interior Point Techniques for Nonlinear Programming." Mathematical Programming, Vol 89, No. 1, pp. 149–185.

CEDR (2012). Adaptation to climate change - Task 16.

Coleman, T. F. and Y. Li. (1994). "On the Convergence of Reflective Newton Methods for Large-Scale Nonlinear Minimization Subject to Bounds." Mathematical Programming, Vol. 67, Number 2, pp. 189–224.

Coleman, T. F. and Y. Li. (1996). "An Interior, Trust Region Approach for Nonlinear Minimization Subject to Bounds." SIAM Journal on Optimization, Vol. 6, pp. 418–445.

Deb K, Pratap A, Agarwal S, Meyarivan T. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans Evolut Comput 2002;6(2): 182-197.

Duffy, L. (2004) 'Development of Eirspan: Irelands Bridge Management System', Bridge Engineering 157 (BE3), Proceedings of the Institution of Civil Engineering, pp. 139-146.

FHWA (2007). Asset management literature review and Potential applications of simulation, optimization, And decision analysis techniques for right-of-way And transportation planning and programming, Report No. FHWA/TX-07/0-5534-1, Texas Transportation Institute, 126p.

Highways Agency. (2008). Climate Change Adaptation Strategy, Volume 1. Information at: www.highways.gov.uk.

IQOA (2012a). IQOA Ponts Campagne d'évaluation 2011 Dossier national. http://www.piles.setra.equipement.gouv.fr/iqoa-donnees-statistiques-r254.html

IQOA (2012b). IQOA Murs Campagne d'évaluation 2011 Dossier national. http://www.piles.setra.equipement.gouv.fr/iqoa-donnees-statistiques-r254.html

Nemmers, C. (2004). Transportation Asset Management. Public Roads Magazine. Data accessed at www.tfhrc.gov/pubrds/july97/tam.htm.

OECD (2001). Asset Management for the Roads Sector.

Orcesi, A.D. & Cremona, C.F. (2011). Optimization of maintenance strategies for the management of the national bridge stock in France, Journal of Bridge Engineering, ASCE, 16(1), 44-52.

Orcesi (2014). Literature review of existing management strategies, Milestone No. M5.1, Re-Gen project - Risk Assessment of Ageing Infrastructure, September, 2014

Petkovic, G. & Thordarson, S. (2012). Adaptation to Climate Change – Task Group under CEDR, Transport Research Arena– Europe 2012

PIARC (2004a) Indicators for bridge performance and prioritization of bridge actions, PIARC technical committee on road bridges (C11).

PIARC (2004b). Asset management in relation to bridge management, PIARC technical committee on road bridges and other structures (C11).

PIARC (2005). Asset management for roads – an overview, PIARC technical committee on road bridges and other structures (C6).

PIARC (2011). Adaptation to climate change for bridges. PIARC technical committee D3 Road Bridges. ISBN : 2-84060-241-5.

PIARC (2012b). Dealing with the effects of climate change on road pavements. Technical committee D.2.

PIARC (2013). Impacts of changes in winter severity on winter maintenance, Technical committee B.5 – Winter service.

Powell, M. J. D. (1978a). "A Fast Algorithm for Nonlinearly Constrained Optimization Calculations." Numerical Analysis, ed. G. A. Watson, Lecture Notes in Mathematics, Springer-Verlag, Vol. 630.

Powell, M. J. D. (1978b). "The Convergence of Variable Metric Methods For Nonlinearly Constrained Optimization Calculations." Nonlinear Programming 3 (O. L. Mangasarian, R. R. Meyer, and S. M. Robinson, eds.), Academic Press.

RIMARROC (2009). Existing methods for risk analysis and risk management within the ERA NET ROAD countries - applicable for roads in relation to climate change State-of-the-art Report, Deliverable 1.

Slovene Regulations (1987). Regulations on the technical normatives for the concrete and reinforced concrete", 1987 (in Slovene).

Terčelj et al. (1988). Systems of observation and methods for evaluation of condition (assessment) of road bridges, three Volume Report, ZAG, 1986 till 1988 (in Slovene).

Wang, X., Nguyen, M., Stewart, M. G., Syme, M., Leitch, A. (2010a). Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure – Synthesis Report. Published by CSIRO, Canberra. ISBN978 0 643 10364 1

Wang, X., Nguyen, M., Stewart, M.G., Syme, M., Leitch, A. (2010b). Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure – Part 1: Mechanisms, Practices, Modelling and Simulations – A review. Published by CSIRO, Canberra. ISBN 9780 4310365 8.

SBRI (2013a). Final report. SBRI-Document No : SBRI-ALL-007-FinalReport.

SBRI (2013b). Handbook. SBRI-Document No : SBRI-ALL-005-Handbook.

Waltz, R. A., J. L. Morales, J. Nocedal, and D. Orban. (2006). "An interior algorithm for nonlinear optimization that combines line search and trust region steps." Mathematical Programming, Vol 107, No. 3, pp. 391–408.

Wang, X., Nguyen, M., Stewart, M.G., Syme, M., Leitch, A. (2010c). Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure – Part 2: Modelling and Simulation of Deterioration and Adaptation Options. Published by CSIRO, Canberra. ISBN 9780643103665.

Wang, X., Nguyen, M., Stewart, M.G., Syme, M., Leitch, A. (2010d). Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure – Part 3: Case Studies of Concrete Deterioration and Adaptation. Published by CSIRO, Canberra. ISBN 9780643103672.

Znidarič,, J. & Perus. I. (1998). Condition rating methods for concrete structures", CEB Bulletin 243, Strategies for testing and assessment of Concrete Structures, Guidance Report, Appendix 1.