**CEDR Transnational Road Research Programme**
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# Re-Gen
# Risk Assessment of Ageing Infrastructure

# Literature review of existing management strategies

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# Executive summary

The transport system represents a fundamental factor for the economic and social development, as it allows the quick, safe and easy exchange of passengers and freight. For the most part, this mobility is sustained by the 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 infrastructure stock.
Bridges, retaining structures and steep embankments are significant critical infrastructure components in terms of safety and functionality for the whole infrastructure. The ageing and deterioration of these elements and the increased traffic intensities and loads, make them the bottlenecks of the transport infrastructure. The inconveniences (congestions) created by the necessary activities for upgrading and repairing these civil engineering structures grow rapidly with increased traffic and age.

The decision to replace or repair these infrastructures, when and how to repair each individual structure, is a common and difficult management issue for asset managers. In particular, asset management systems are used to manage transportation infrastructure and help guide policy.
In this context, this reports (i) details the main components of current asset management tools, by illustrating each time the concepts presented through several examples, (ii) reviews recent developments in asset management methodologies, and (iii) identifies works in literature that tackle the issue of climate change on asset management.

# 1 Introduction

The majority of infrastructure components for road transport system was 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 user. 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.

In this context, asset management systems have been developed by many countries to serve as a tool to track inventory data and analyze maintenance and improvement needs for existing structures. The objectives of such systems include the combining management, engineering, and economic input to assist in determining the best action to take on all structure elements on the network over time. The actions can involve enhancement of safety, providing additional capacity, both load and traffic, and preservation of existing facilities.

A literature review on asset management practices is conducted in this report which describes and illustrates the main modules of asset management systems, details recent developments in asset management methodologies, and reports recent studies that tackle the issue of climate change on asset management.

# 2 Asset management concepts

## 2.1 What is asset management?

Asset management is an emerging effort to integrate finance, planning, engineering, personnel, and information management to assist agencies in managing assets cost-effectively (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 disturbance during road works (PIARC 2005).

The main objective of asset management is to improve decision-making processes for allocating funds among an agency’s assets so that the best return on investment is obtained. To achieve this objective, 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).

Figure 1 illustrates the strategic asset management framework within which jurisdictions may select their priorities for improving their approach to road management (PIARC 2005).

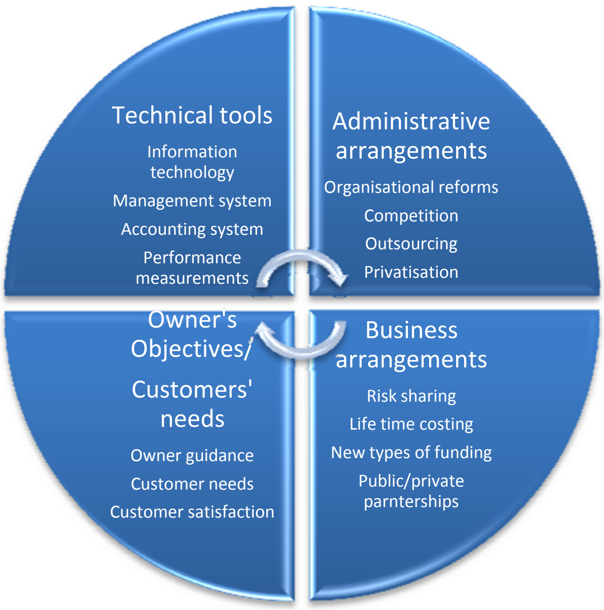



**Figure 1. Business strategy.**

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. Better definition of the owner's objectives and understanding of users' needs and satisfaction levels may be a high priority in some countries. Finally some jurisdictions may choose to pursue different costing procedures and funding alternatives. Regardless of priorities, and selection of components considered for implementation, the adopted approaches are best determined in the context of a strategic asset management framework which will allow for futures integration of the respective elements and for flexibility to incorporate additional asset management features and processes in accordance with changing needs and directions, as they develop in the various jurisdictions."

## 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 e.g. rest areas, parking areas and loading areas),
- unfinished road projects and structures.

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

## 2.3 Components of an asset management system

An asset management system undertakes several procedures, enhancing 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 estimations of their current value.

More specifically, a typical asset management system consists of various modules (Figure 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 Figure 2 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. extent of maximum traffic congestion, demands on safety, demands on intermodal interactions, demands on general customer satisfaction,…). 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 represent the third pillar of an asset management framework and includes e.g. the total budget allocated annually or multi-yearly for the entire network and division by division.

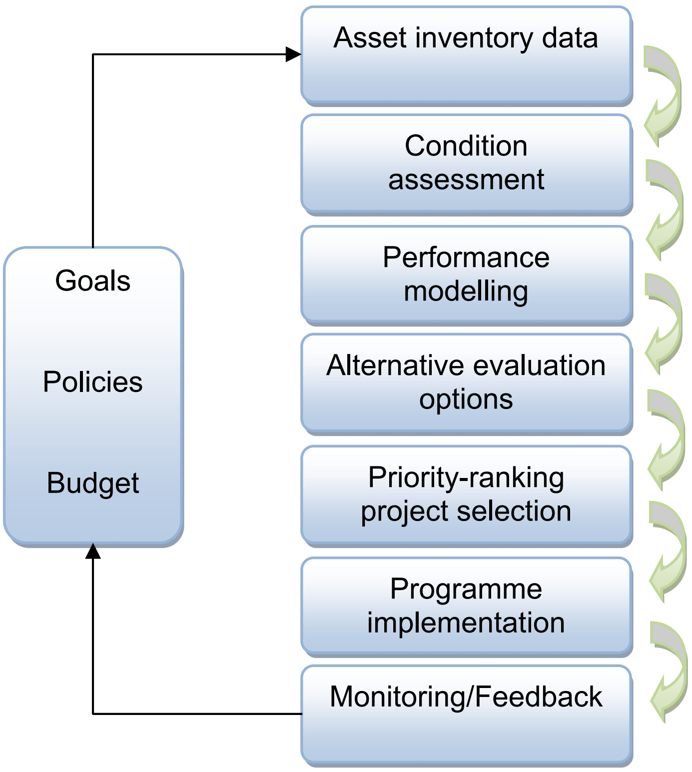



**Figure 2. Components of an asset management (PIARC 2004b).**

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 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
Knowledge of current condition is needed to assess the asset network current scenario. 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 effective asset management. 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" analyses are 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, benefit/cost 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 can support 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. Frequent modifications can damage its credibility. Major modifications to the system, including changes in database requirements, prediction models, economic analysis techniques, and reporting tools, deserve careful evaluation. 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 Review of existing management systems for bridges*

The European project BRIME (2001) detailed several bridge management systems (BMS). The countries included in this comparison were **France**, **Germany**, **the UK**, **Norway**, **Slovenia**, **Spain**, **Denmark**, **Finland**, **the USA** and **Canada** (Calgaro 1997, Woodward et al. 1999). Eight of the ten countries listed above use a computerized form of BMS, except for **Germany** and **Spain** (Der Bundesminister fur Verkehr 1982). **France** uses a partially computerized BMS (Calgaro 1997) and the BMS's vary between two to twenty years in age.

Countries that have a computerized BMS generally use the commercially available ORACLE software as their database, with the **UK** and **Slovenia** as exceptions (Znidaric et al. 1995). There are no clear guidelines drawn out for bridge management in **Slovenia**, compared to other countries having documents that give instructions concerning this. **The UK** uses a maintenance manual and **France** uses a type of management instruction. **Norway**, **Denmark**, **Finland** and **USA** (New York) have user manuals provided (Andersen 1990, Børre 1997). **Germany** and **Spain** both do not have any special guidelines for their BMS's (Vorshrift 169/89, 1989).

A more detailed extract of this comparison is presented below (see the final report of BRIME project for further details):

**In the USA**, a variety of bridge management systems are used and the methods developed for decision making are summarised below:

- PONTIS. The optimum policies are developed at a network level based on the minimum expected life-cycle costs over an infinite planning horizon.
- BRIDGIT. The bridge level actions are developed by minimising the expected lifecycle costs over a 20 year period. The optimum sequence of actions and the optimum time to take the action are considered. Actions may be triggered by the need for upgrading, rehabilitating deteriorated structures, replacement, etc. Benefits are determined as cost savings to the user.
- State Specific Systems. Several states have developed their own BMS: Alabama, Indiana, New York, North Carolina and Pennsylvania.

**In France**, decisions are made using engineering judgement with several levels of control both technical and financial.
Likewise, engineering judgement is used in **Germany and Spain**.

**Great Britain** uses cost benefit analysis, future needs and engineering judgement.

**In Denmark,** the Danish road directorate has developed an assets management system called DanBro. Also commercial infrastructure asset management systems are used, such as SMART developed by Ramboll. SMART provides users and decision makers on all levels of the organization with the necessary tools and information for an efficient management:
- overview of assets and their technical properties,
- overview of condition,
- overview of maintenance needs,
- overview and management of requested, on-going and finalized activities,
- overview of short and long term budget needs,
- overview of documents,
- easy web access to the system and the data.

**In Norway**, proposals for repairing damage are based on a description of the damage and the condition assessment, and are prepared using a coding system describing the type of works and processes involved in the repair. Cost estimates are prepared for the proposed action, and an indication is given as to the year in which these activities should be undertaken so as to ensure that the specified standard is maintained.
When the cost of repairs recommended following a major inspection or special inspection exceeds 20% of the bridge replacement value, alternative strategies should be investigated. At least two different strategies should be investigated depending on what is available. In addition to maintenance costs, road user costs and any costs to society, if affected by the various strategies, are also taken into account.

The following strategies may be considered:

- temporary action: minor repairs that enable major works or bridge replacement to be postponed;
- major action: extensive repair work over a short period that significantly extends the remaining service life of the bridge;
- new element/bridge: no repair work undertaken; however, the existing element/bridge is replaced at the end of its service life.

For each strategy different technical solutions may be considered. When maintenance costs exceed 50% of the replacement value, the third strategy must be considered.
The net present value of the selected strategies is estimated and this forms the basis for selecting the optimal strategy. Factors that normally do not enter into cost estimate are also included before the final decision is made. Such factors may include: age of the bridge, remaining service life, carrying capacity, bridge width/road curvature, vertical clearance, traffic safety, future usage, aesthetics, historic value, etc.

In **Finland**, the Finnish Bridge Management System (BMS) consists of two different parts: the Network Level BMS and the Project Level BMS (Söderqvist & Veijola 1999). The Project Level BMS, which deals primarily with individual bridges, uses the recommendations and goals from the network level to decide on the repair measures in individual repair projects to create repair and reconstruction programmes. The project level system is the key tool for everyday bridge repair planning in the road districts. The system helps the bridge engineer to plan and schedule the repair projects for individual bridges based on the recommendations and the damage data in the database. The system works with repair and reconstruction programmes. In connection to these programmes different alternative studies and profitability calculations can be made. For example, analyses concerning bridge structural parts and bridges remnant life will be available. A ranking system is used when picking out the bridges which need either repair and rehabilitation or reconstruction measures. An index describing the repair needs of individual bridges was taken in use for the purpose of arranging the bridges in an urgency order in the work programme. This repair index is a function of a bridge structural part's estimated condition, damage class and the repair urgency class. The programme is prepared so that the condition target can be reached by following the given repair recommendations.

**In Germany**, the German Federal Ministry of Transport has developed a comprehensive management system for structural maintenance. The planned management system is to provide the Federal Ministry with an overview of the current condition of structures at the network level, estimate future funding requirements and develop strategies for achieving long-term objectives and carrying out routine maintenance. In addition, it should provide the state bridge authorities with the programmes of work required to obtain improvements at the project level that maintain structures in an acceptable condition and meet network level strategies, long-term objectives and budgetary restrictions.

The first task at the state level is to develop and compare the maintenance options for each structure for the planning period i.e. the planning process. This results in a prioritisation of maintenance measures at the project level and a budget estimate, i.e. a list of all the projects scheduled for the planning period at the state network level. The resulting program is then fine tuned at the federal network level in the controlling process. This is undertaken to ensure that the final programme meets specified network level objectives (Haardt, 1998).

The planning process consists of recording and evaluating the condition of each structure in accordance with the German inspection rules DIN 1076 and RI-EBW-PRÜF. (These are guidelines produced by the Federal Ministry of Transport, Building and Housing for standardised recording, condition assessment and investigation of the results of inspections according to DIN 1076.) Structures in a critical condition are given priority for maintenance. The remainder are subject to the maintenance planning process and the results from the inspections are used to determine the requirements for maintenance. This may require an additional evaluation of the structure if the results of regular inspections are not detailed enough for maintenance planning. This could be a structural assessment or a more detailed inspection. The ideal times for maintenance are determined on the basis of deterministic deterioration models for the individual bridge elements. Suitable maintenance options are identified and the resulting changes in condition that would be achieved are predicted. Alternative actions are then ranked using cost/benefit analyses to determine the preferred solution at the project level. A network-wide comparison of cost/benefit-ratios is used to provide an urgency rating for the preferred option for the planning period. This is used to determine the financial requirements at the network level and results in the first draft of the maintenance program. Budgetary restrictions make it necessary to optimise this maintenance program at the network level. In some circumstances, this optimisation will change the proposed measures at the project level if the budget is not sufficient to carry out all the proposed maintenance measures.

The controlling process is carried out at the federal level and uses information from the Federal Ministry of Transport database (BISStra) and the results from the state level planning process to develop the final programme. As part of the controlling process, expenditure forecasts are prepared, analysed and updated, the draft maintenance programs are analysed and rated, and annual expenditure on maintenance that has previously been undertaken is reviewed. This information is used to determine the available budget, amend the proposed measures and update the technical rules (DIN 1076, ZTV-ING, RI-EBW-PRÜF).

The maintenance programmes are implemented by the state administrations. They plan and produce the required documentation for carrying out the works. Factors that are taken into consideration include the ability of the agencies to resource the work, and the possible combining of maintenance options, for example treatment of a number of bridges along a length of road. The results are submitted to the following year’s planning and controlling processes. This planning module can be extended to include project preparation, administration of measures and documentation.

A phased plan for the completion of the system has been prepared and it is planned that it will be fully implemented at both Federal and State levels by 2005 (Haardt, 1998).

**In Poland**, Since 1989, Poland has developed a management system for maintenance planning, which includes decision-making procedures at various organisational levels i.e. local, national etc. The basic function is for planning maintenance over a 1-year period, taking into account data from the bridge inventory, construction details and bridge condition. To optimize the allocation of available resources, linear programming is used, taking into consideration the replacement value of all the bridges in a region, the condition of the bridges and additional statistical data such as the number of bridges and their surface area. These results are used to determine the annual maintenance costs on the basis of cost tables. As part of the optimisation process, the available resources are distributed among the individual bridges. A number of parameters are taken into account including:

- costs carried by the organisation responsible for running/managing the network and users,
- comparison of service-life costs with the cost of new construction,
- technical criteria (i.e. simplicity of the repair works),

- durability (i.e. high deterioration rate in an aggressive environmental),
- influence of traffic (i.e. high volume of traffic or absence of alternative routes),
- urgency of the repair, restrictions etc.

In Slovenia the decision when maintenance work is needed is based on inspections and engineering judgement, increased traffic flows and the importance of the bridge to the region.

**In Sweden**, the Swedish bridge management system contains inter-disciplinary strategies for planning and control measures, as well as operative planning and implementation of measures. Two models are available for operative planning and procurement. The first model is used for routine maintenance, i.e. preventive maintenance and minor measures. The second model, called SAFEBRO, is used for major maintenance. A database that contains the technical solutions available and their costs support the planning procedure.

**Switzerland** is developing the KUBA-MS system as a prototype BMS. The system is intended to fulfil the following objectives:

- to determine the ideal maintenance policies, in economic terms, with and without budgetary constraints
- to determine the consequences of deviating from this strategy
- to take account of the costs incurred by operating companies and users
- to determine the optimum measures for any planning period
- to determine both the short-term and medium-term financial requirements
- to indicate the affect of different budgetary restrictions on the average structural conditions.

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, practice in relation to bridge management 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 the above reference or at http://www.nra.ie/

More recently and through the responses to questionnaires submitted by more than twenty countries, the World Road Association provided an analysis of the various network prioritization approaches adopted by countries and highlighted basic data and processes required to prioritize bridge maintenance interventions at the network level (PIARC 2012a). It follows that Bridge management system(s) (BMS) are often developed in-house by individual road administrations. Among the twenty countries considered in this report, **UK** seems to have been the first road administration to develop a BMS (1984) followed by **Finland** (1986) and **Denmark** (1987). It is clear from the submissions received that the extent of BMS development varies greatly and most have adopted a staged approach to system development to meet evolving needs for network level analysis and management. There are examples of knowledge and system transfer where developed BMS have been adopted by other countries either in the original or customized forms (PIARC 2012a).

## 2.5 Recent developments for asset management

Traditionally, the management systems to be followed within one jurisdiction is selected by the responsible road network manager based on a number of well thought through future scenarios of what would likely happen over the coming years. These scenarios are developed for each infrastructure manager based on information provided by civil engineers (for the infrastructure), and environmental engineers (for the natural hazards) principally in deterministic form. The uncertainty with respect to the scenarios is captured through the development of multiple scenarios. Although the infrastructure managers works with the best intentions this methodology does not allow for a systematic and rigorous investigation of all future scenarios, taking into consideration the uncertainties related to demand and supply, and the determination of the optimal management strategies, i.e. the one that would maximize the benefit to all stakeholders, and therefore the one that will maximize the competitiveness of road transport.

Developments in many scientific and technological fields over the last 20 years make it only now possible to optimally manage road networks taking into consideration the uncertainties in more systematic and rigorous ways than has traditionally been done in the past. These developments include:

- computerized infrastructure management systems, where computerized systems can now allow the determination of optimal management strategies for each element of an object and can then aggregate it into work program, albeit taking into consideration principally infrastructure manager costs and gradual deterioration of the elements (Golabi & Shepard, 1997), (TRB, 2009),
- operations research methods, where directed graphs have now been successfully used to determine the optimal placing of a work site on transportation networks (Hajdin & Lindenmann, 2007) (Durango-Cohen & Sarutipand, 2007) (Sarutipand, 2008), and risk analysis, which has been used to take into consideration the uncertainties related to the occurrence of natural hazards, such as the use of extreme value theory to predict the recurrence of the flood waters that may result in damages to buildings (Faber & Stewart, 2003) (Faber, 2005), and the probability of loads exceeding the load carrying capacity of the infrastructure objects as they change over time (Stewart & Erich, 2003), (Cremona, 2011)
- considering uncertainty in decision making, where financial analysts have established progressively sophisticated methods to evaluate real options, explicitly taking into consideration future uncertainties (Schwartz & Trigeorgis, 2001), engineers have increasingly applied Petri Nets to evaluate complex systems to integrate uncertainty in their decision making, as well as how this uncertainty changes over time (Ayyub & Gupta, 1998) (Fellin et al., 2005) (Straub & Kiureghian, 2010), and developers of management systems have begun to implement multi-criteria analysis in management systems (Neves et al., 2006) (Neves et al., 2006) (Frangopol & Liu, 2007) (Okasha & Frangopol, 2009) (Okasha & Frangopol, 2010).

  These developments are significant steps towards the next generation of infrastructure asset management systems, where management strategies will be determined for all structures simultaneously, taking into consideration how the objects function together to provide users with an adequate level of service.

From an operational viewpoint, PIARC (2008) proposed some recommendations for implementation of the Asset Management approach for management of road networks (Road Asset Management, RAM). It proposes (i) a discussion on the difference between RAM and traditional Asset Management systems with technical tools and administrative and business arrangements, (ii) a description of basic concepts like output and outcome together and their main properties, and (iii) a discussion on the role of the cooperation in Asset Management between road administrations, stakeholders, contractors and partners, together with the role of performance indicators, and the road corridor approach. More specifically, it is stated that RAM should be an integrated approach to the management of road assets optimizing over its many different aspects: components, goals, stakeholders, present and future outcomes.

# 3 Detail of modules in current asset management systems

This section proposes an illustration of the following modules, introduced in Figure 2:

- asset inventory data (section 3.1),
- condition assessment (section 3.2),
- performance modelling (section 3.3),
- alternative options evaluation (section 3.4).

## 3.1 Asset inventory data

The inventory of the asset and of its components is the first step in the development of the management framework. As an example (PIARC 2012a), while bridge management systems generally include culverts, there are examples of more extensive “structure management systems” in some countries that include other assets, such as tunnels (Sweden, UK, Denmark, Western Australia), retaining walls (UK), gantries (Western Australia, UK, Vienna), high lightning masts (UK) and noise barriers (Vienna).
Also, the number of structures included in one asset varies depending on the extent of the road network. PIARC (2012b) reports that “the extremes, among more than twenty countries which responded to a questionnaire on bridge management system (BMS), range from the largely rural Northern Territory of Australia that manually manages 200 bridges while the developed state of Virginia in the USA manages some 20,280 bridges and culverts in its BMS. Additionally, the extent and sophistication of management systems is dependent on the size and complexity of network that has to be managed. In most countries, the principal BMS structure inclusion criterion is defined by minimum span length however the minimum waterway area is sometimes specified as a supplementary criterion. In the event that other structure types are included in the BMS then specific inclusion criteria are specified in that regard.”
As mentioned in section 2.3, asset inventory data should contain:

- drawings,
- building year,
- price,
- different types of inspection reports,
- calculations,
- main dimension,
- photos,
- maps,
- memos,
- tender documents,
- etc.

The example of the inventory of the bridges and retaining walls of the French national road network managed by the French Ministry of Transportation (IQOA 2012a,b) is presented in the following. This inventory is performed in link with the IQOA inspections (quality assessment of engineering structures) which are further described in section 3.2.4. The illustration proposed in this section is only one portion of what inventory data means as it is explained in section 2.3. The objective herein is more to graphically show the information

which can be synthesized to give an overall view of the stock. The reader can find additional information on the inventory of this French network in (IQOA 2012a,b).
For bridges, the evolution of the stock between 2007 and 2011 is shown in Figure 3. The breakdown by materials is then provided in Figure 4 (per number of bridge) and in Figure 5 (per surface area).

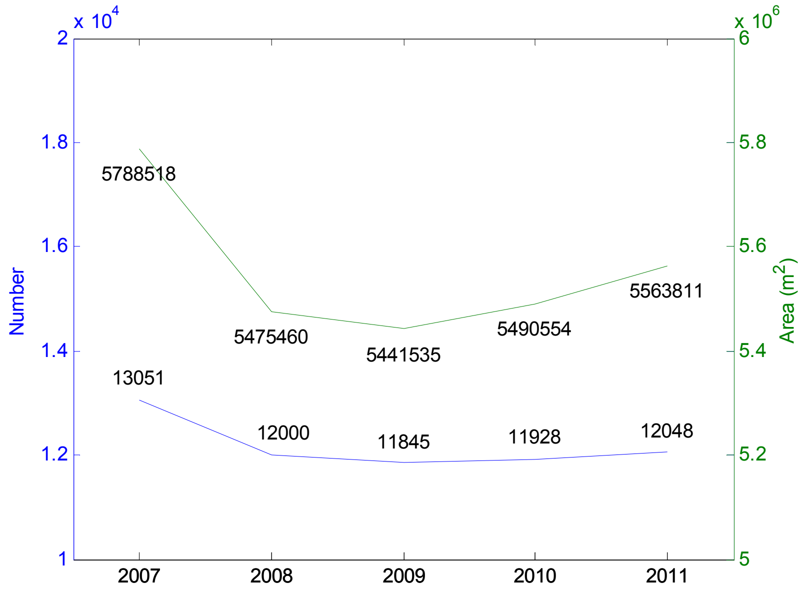



**Figure 3. Evolution of the bridge stock managed by the French Ministry of Transportation.**

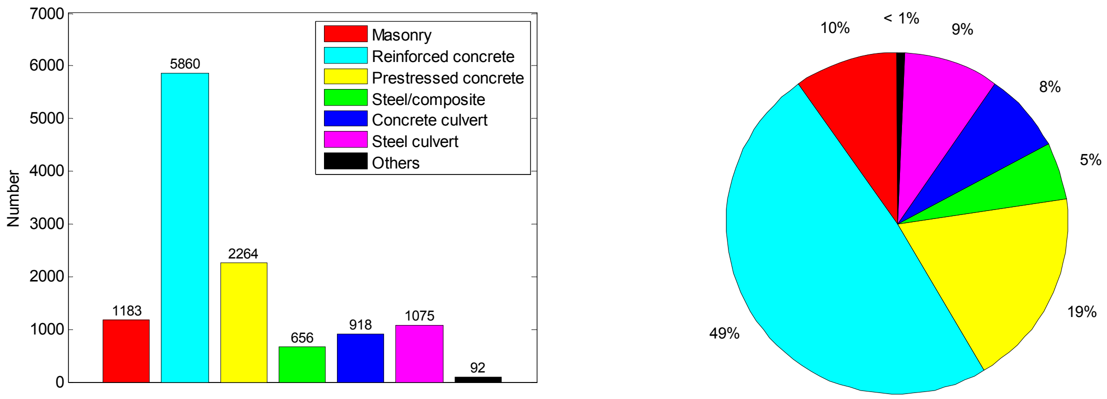
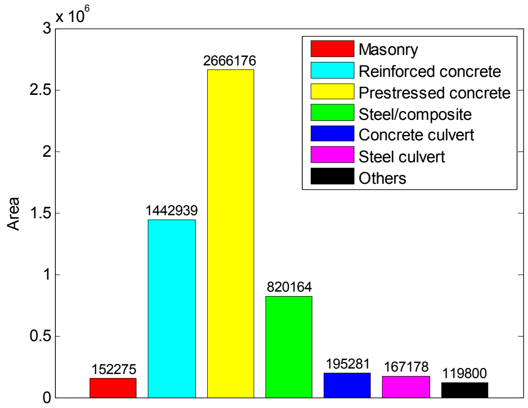



**Figure 4 Breakdown by material of the bridges (in number).**



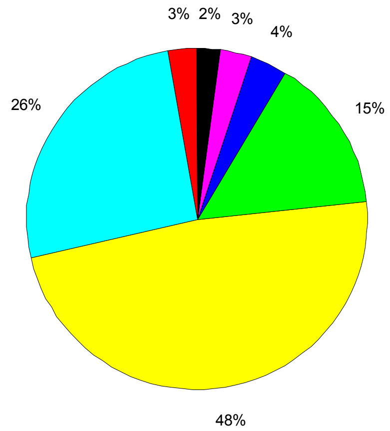




**Figure 5 Breakdown by material of the bridges (in surface area).**

Similar information are shown below for retaining walls. The evolution of the stock between 2007 and 2011 is shown in Figure 6.

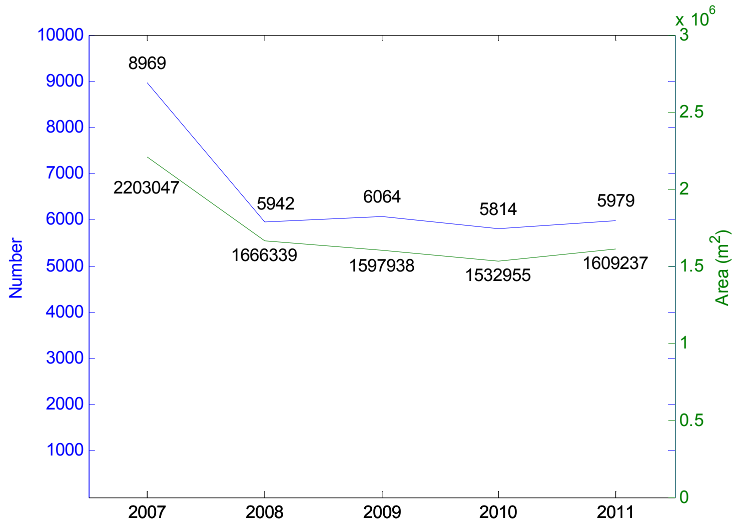



**Figure 6. Evolution of the retaining wall stock managed by the French Ministry of Transportation.**

The breakdown by materials is then provided in Figure 7 (per number of walls) and in Figure 8 (per surface area) for the list I of walls. List I includes dry-stone walls, jointed stone, concrete gravity walls, gabions (stone and steel mesh, precast concrete units and cantilever walls).

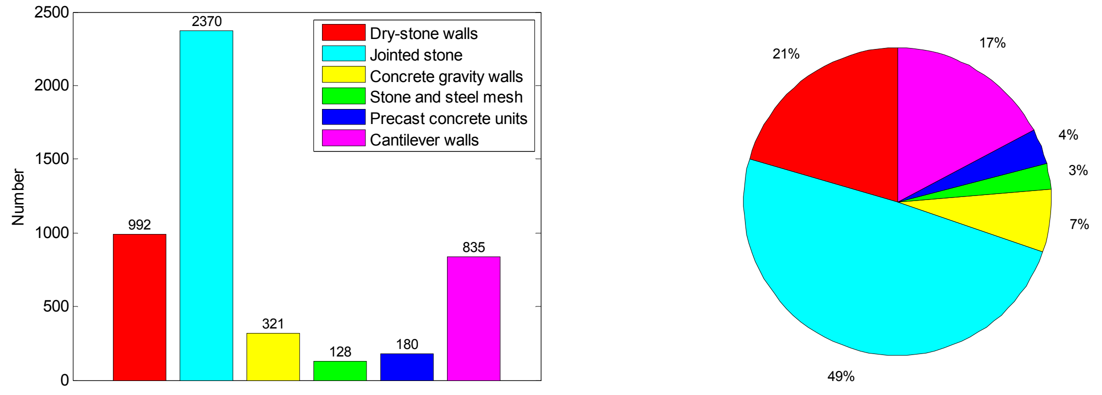



**Figure 7. Breakdown by material of the retaining walls (in number) – list I.**

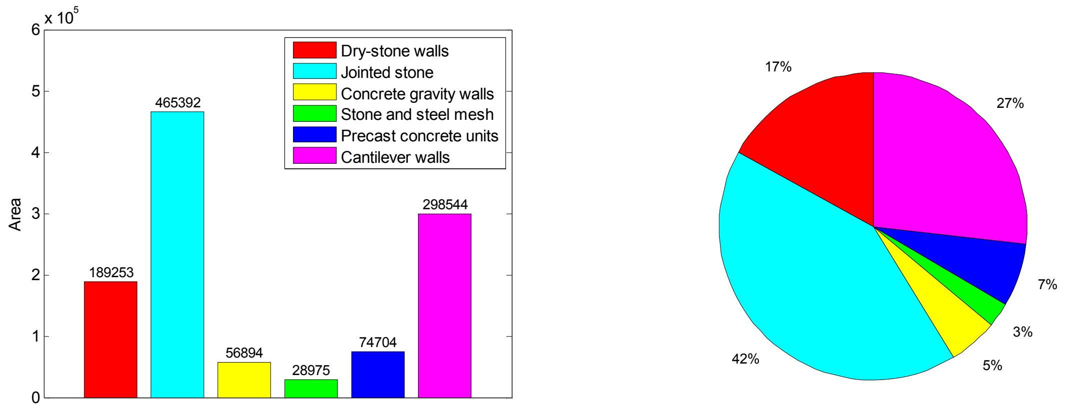



**Figure 8. Breakdown by material of the retaining walls (in surface area) – list I.**

The breakdown by materials is then provided in Figure 9 (per number of walls) and in Figure 10 (per surface area) for the list II of walls. List II includes steel sheet pile, slurry walls, composite walls, earth walls reinforced by steel elements or geosynthetics, soil nail walls and anchored beams/shells.

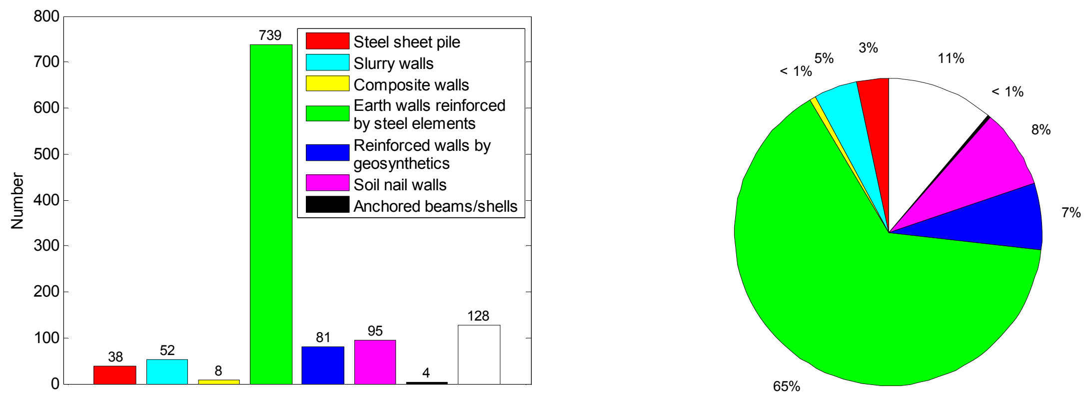



**Figure 9. Breakdown by material of the retaining walls (in number) – list II.**

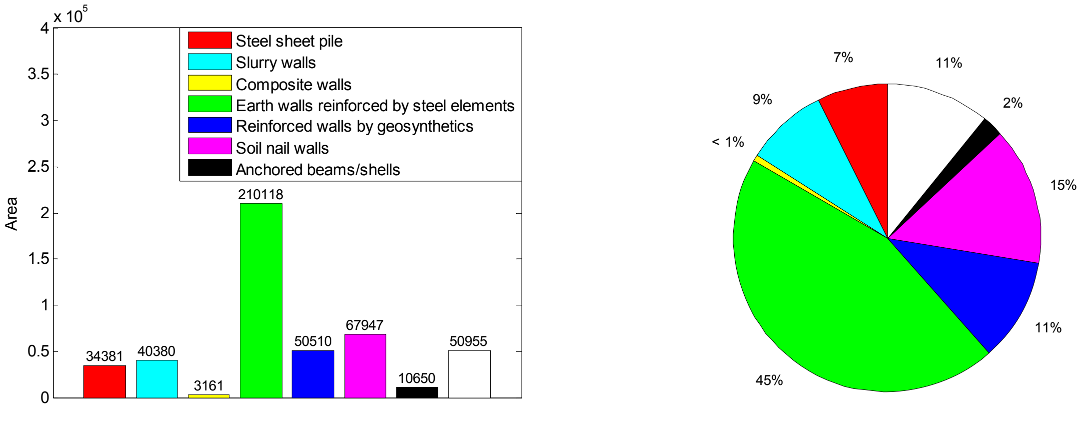



**Figure 10. Breakdown by material of the retaining walls (in surface area) – list II.**

## *3.2 Condition assessment*

Over the last decades considerable problems have arisen due to deterioration of the road network in Europe. This has occurred for several reasons: ageing of the infrastructure stock, increases in traffic load, environmental attack and sometimes due to poor design, detailing and construction of the structure. In particular, the most common form of deterioration on concrete structures is corrosion of the reinforcement caused by the ingress of carbon dioxide or chloride ions (BRIME 2001). The latter penetrate structures in marine environments or in countries with harsh winters, where de-icing salts are used on roads during winter. De-icing salts either penetrate through the deck or are sprayed onto the substructure of overbridges by passing vehicles. Concrete structures also deteriorate due to cyclic freezing and thawing during the winter. Chemical reactions within concrete caused by sulfate attack or alkali silica reaction can also cause severe degradation of the concrete surface or structural element itself. A more detailed description of the causes of deterioration is given in section 3.3.1. To determine which structures require maintenance, it is necessary to undertake a systematic programme of inspections. One of the main purposes of these 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).

### *3.2.1 Inspection framework*

The main objective of structural assessment is to monitor the extent and severity of any defects or deterioration that is present and to determine the optimum time for intervention. That is, to determine the appropriate time for any repair or maintenance that is required to preserve the condition of the structure within acceptable limits. An additional objective is to evaluate the efficiency of different repair techniques, the suitability of different materials used in repair work and their application.

To deal with all these problems, several inspection procedures have been applied in different countries, though In general, the procedures used are similar. For illustration, basic types of bridge inspection used in France are detailed below (BRIME 2001).

Superficial/routine inspections are carried out by maintenance personnel who are familiar with the safety procedures for working on the highway but do not have specialist knowledge of bridge pathology. The aim is to observe major defects  (for example damaged safety barriers or broken drainage systems) on and under the bridge. This is done continuously and a note is made of any observations i.e. date of inspection and details of any defects.

General inspections are a visual examination of all the accessible parts of a bridge but without the use of special access equipment. Normally, they are undertaken by technicians who have received some training on bridge inspection. A more qualified inspection team is required for more complex bridge structures. The aim of the inspection is to detect all defects that can be seen from the ground and to evaluate the condition of the structure. The recommended frequency of general inspections is one to three years. An inspection report must be prepared that should, if required, give a recommendation for a more detailed inspection. If a general inspection is carried out after a major inspection (see below), and no repair or maintenance work has been undertaken since the previous inspection, only the observed defects are assessed in the inspection report. The evaluation of other defects observed during the previous major inspection but which cannot be properly evaluated during general inspections, are not changed.

Major/principal inspections are a visual inspection of all parts of the bridge structure. They are carried out by qualified bridge engineers with experience in bridge maintenance. The aim is to get within touching distance of all parts of the bridge and make a visual assessment of the condition. Therefore access must be provided and specialised equipment may be required.

The inspector should identify and record poor construction details as well as defects. The recommended frequency for major inspections is at least five to ten years, although they could be undertaken more frequently depending on the condition of the structure and its load carrying capacity. For example, more frequent inspections would be required on structures with excessive deflections and settlement, or where joints opened under load. This type of inspection may include some measurements e.g. vertical displacement, settlement, chloride content at most critical elements of the structure, the scope of which depends on the condition and complexity of the structure.

In-depth inspections are performed on bridge structures that are undergoing repair. They are usually carried out on complex structures and may cover the whole structure or be restricted to the components or elements that are likely to be affected by the repair. Usually the inspection includes extensive measurements both on site and in the laboratory which are undertaken to determine the cause and extent of the damage or deterioration and provide data

Special Inspections are carried out where there is a particular problem or cause for concern either found during an inspection (e.g. uncertainties regarding damage type and damage extension and future development) or already discovered on other similar bridges. They are also carried out for a variety of other reasons, for example: structures strengthened by the use of bonded steel plates, bridge foundations after flooding, and structures after earthquakes.

For major/principal, in-depth or special inspections, a full report is required giving a description of the defects, an assessment of the condition of the structure and recommendations for special - or detailed - inspections and urgent repairs. The extent and severity of any defects should be described in sufficient detail to enable a reasonable estimate to be made of the cost of the repair work.

The way in which the results obtained during an inspection can be used is presented graphically in Figure 11.

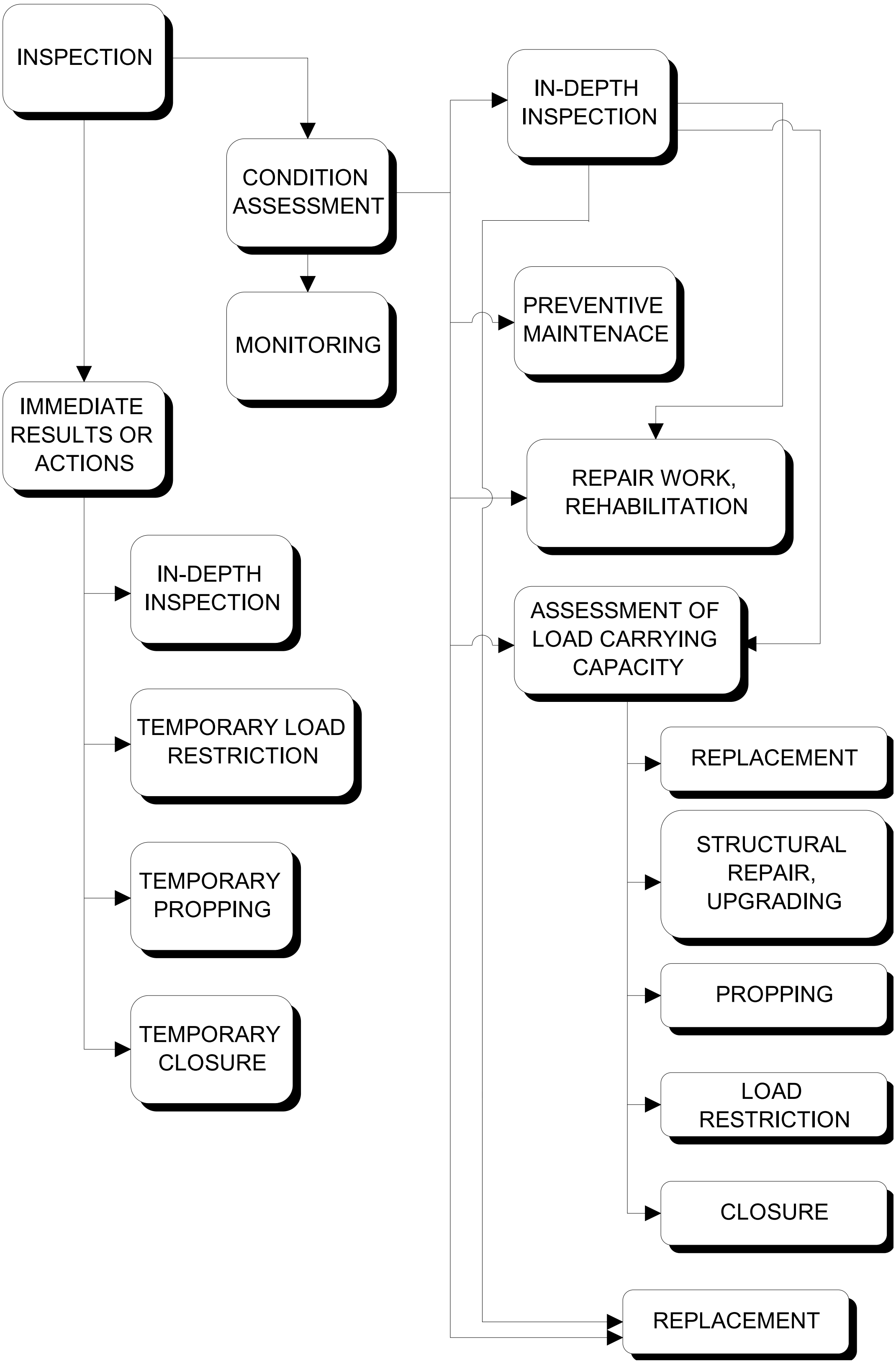



**Figure 11. Flowchart showing use of data on condition assessment (BRIME 2001).**

### 3.2.2 Bridge health index (BHI)

BHI is one of the most common indices applied in bridge rehabilitation management (Fwa & Farhan, 2012). According to this index, each bridge is assigned a condition state which is determined for each bridge element, applying five discrete ratings from 1 to 5 where 1 and 5 represent the best and the worst condition states, respectively (AASHTO 1997b). Therefore, according to the estimated condition state for each bridge element, first BHI is calculated for each bridge element and then applying all BHIs, the overall BHI for the whole bridge is calculated. In most cases, the BHI for each bridge has a minimum threshold which is considered as a constraint in optimization problem. BHI as a performance measure for resource allocation reflects element inspection data in relation to the asset value of a bridge or networkof bridges (Thompson 2000, Shepard & Johnson 2001, NCHRP 2007, Fwa & Farhan, 2012).

### 3.2.3 Physical Condition

According to the Asian Development Bank (2000), deterioration of the physical condition of the road network elements is the result of inadequate financing of the road subsector in combination with damage from civil conflict and major natural disasters. Since physical condition states are standardized and valued in the same way across the transportation agencies, they are among the easiest indices in bridge rehabilitation management (Thompson, 2000). In most cases, a bridge in poor physical condition or one that is already scheduled for structural or functional rehabilitation is given a higher priority for retrofitting (FHWA, 2008). Physical condition ratings are used to describe the existing, in-place bridge as compared with the as-built condition. The ratings are based on the evaluation of the materials and the physical condition of the deck, superstructure, and substructure (FHWA, 2008) and may vary from 1 to 5.
It is to be noted that BHI (in section 3.2.2) is a quantitative tool that measures the overall condition of a bridge while “physical condition” ratings are used to qualitatively describe the existing, in-place bridge as compared to the as-built condition. A lower health index means that rehabilitation tasks would be required to improve the bridge to an ideal condition. However, a lower physical condition demonstrates the poor conditions of the materials used in the bridge including the condition and the appearance of the deck, superstructure and substructure components.

### 3.2.4 Condition assessment of the IQOA bridge stock

This section presents an example of condition assessment framework in the case of the bridge stock on the national road network in France. The Roads Directorate initiated in 1994 a new scoring system, named IQOA quality assessment of engineering structures to assess the structural condition of the national bridge stock (see section 3.1 for the inventory of this stock). The IQOA scoring system was developed to provide a global assessment of the national bridge stock by assessing bridges every 3 years (i.e., by applying each year IQOA inspections on a third part of the asset (Orcesi & Cremona 2011). It is noted that 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 section 3.2.1. During an IQOA inspection, several components are inspected: equipments (pavements, footways, cornices, retaining devices, 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 component and structural part (see Table 1). The final score is then the worst score of all components. The IQOA score is not considered in France as a condition index in the sense that all the defects have the same weight in the final IQOA value for a bridge. For a specific bridge, the IQOA score covers various problems from structural ones to nonstructural ones.

**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 main objective of the IQOA program is to provide a snapshot of individual bridges' condition, and then, a snapshot of the overall bridge stock quality (by aggregating all IQOA scores). The difference of defects between IQOA scores 2 and 2E and IQOA scores 3 and 3U is substantial. Scores 2 and 2E represent serviceability defects while the two others represent structural deficiencies. The target values of the quality indicators to be reached within 15 years (expressed as a percentage of the entire bridge stock deck area) are provided in the third column of Table 2.

**Table 2: target values of the quality indicators (as prescribed by the Roads Directorate in France).**

| Index | Objective | Target value within 15 years |
|---|---|---|
| $I_3$=1+2 | Routine maintenance to prevent repairs | $\geq$ 55% |
| $I_4$=2E | Specialized maintenance to prevent repairs | $\leq$ 30% |
| $I_5$=3+3U | Structural maintenance to prevent collapse | $\leq$ 15% |
| $I_6$=3U | Urgent structural operation to prevent disruption and to ensure safety of the road network | $\leq$ 1% |

Figures 12 and 13 present the evolution of the breakdown of bridges, per number and surface area, respectively, between 2007 and 2011 (nonscored bridges "NE" represent bridges under rehabilitation, new bridges…).

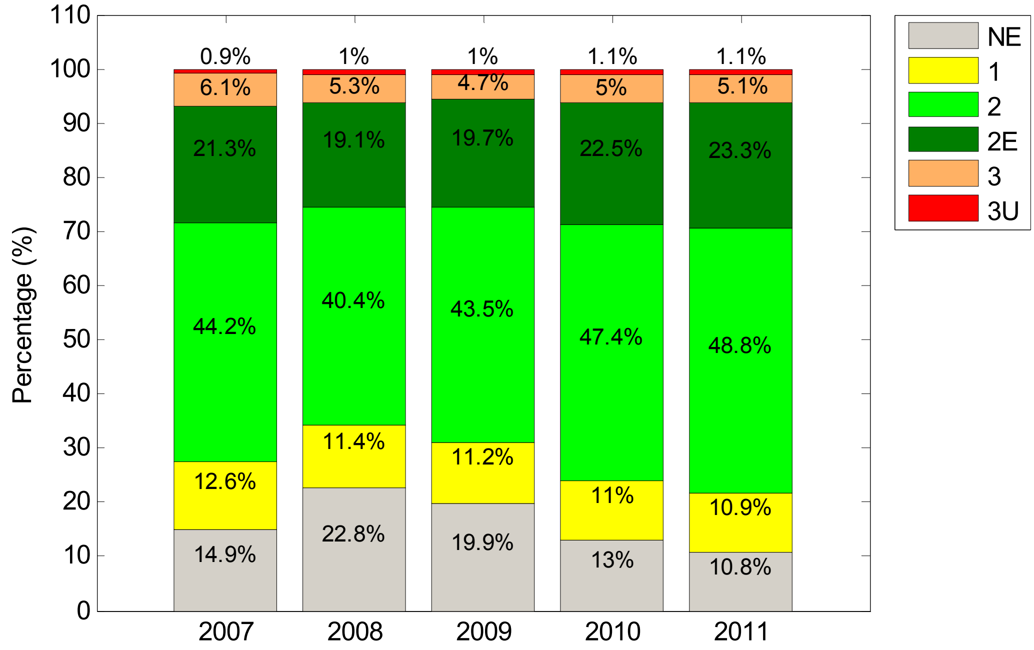



**Figure 12. Percentage of bridges in each score between 2007 and 2011.**

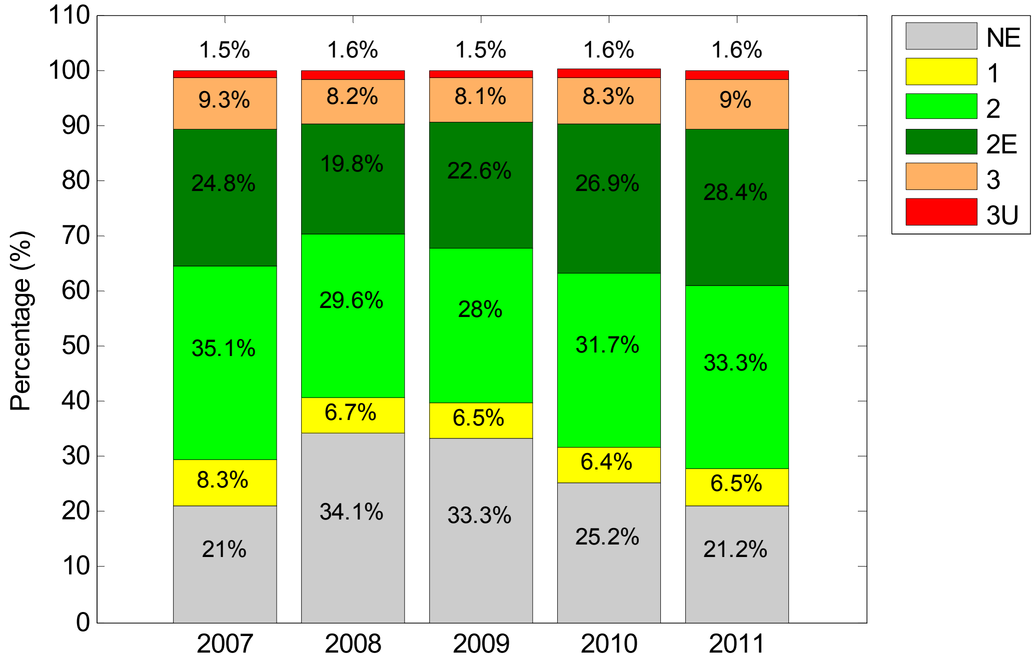



**Figure 13. Percentage of surface area of bridges in each score between 2007 and 2011.**

## *3.3 Performance modelling*

The BRIME project (BRIME 2001) describes the concept of performance during the life-cycle of a structure:

The phases of the service life of a structure are dictated primarily by loss of structural performance, although loss of serviceability (for example, due to defective non structural components) can be just as important. During its whole life, a structure subjected to various repairs or strengthening work may reach a minimum acceptable safety level (Figure 14), this point corresponds to the end of the service life if no other rehabilitation action is conducted.

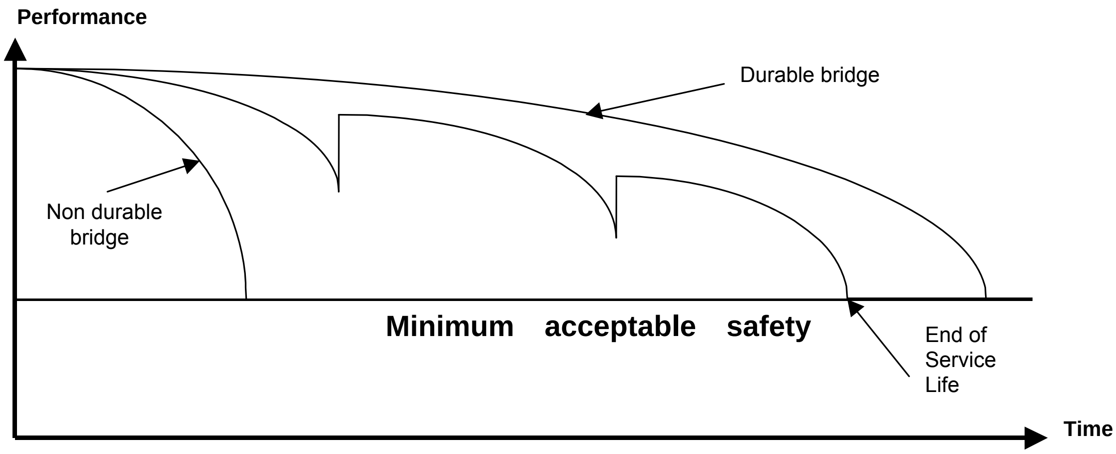



**Figure 14. Performance of a bridge as a function of time. (the vertical steps correspond to maintenance actions). The performance may be represented by the condition rating or the load carrying capacity (BRIME 2001).**

The convex form of the curve is due to the deterioration process that transfers the load supported by the deteriorated areas towards the sound parts of the bridge; this transfer is in general irreversible since repairs do not restore the initial stress state within the entire structure. The objective of an effective maintenance strategy is therefore to increase the service life of the bridge at minimum cost. The longer the service life without incurring substantial maintenance costs, the more durable the bridge may be considered to be (BRIME 2001).

### *3.3.1 Degradation affecting structural performance*

#### 3.3.1.1Corrosion of the embedded reinforcement steel

Long-term durability of reinforced concrete (RC) structures has become one major concern in view of the vast amounts of money required to maintain the infrastructures in a serviceable state. In particular, corrosion of the embedded reinforcement steel, resulting from chloride ingress or atmospheric carbonation, is a matter of considerable concern which irreversibly affects the serviceability of RC structures.

The phases of the service life of a structure are dictated primarily by loss of strength, although loss of serviceability can be just as important. At some point in a deteriorating structure, a minimum acceptable level of performance may be reached and this defines the end of the service life. This is illustrated schematically in Figure 15, which gives an example of a structure that is deteriorating due to corrosion of reinforcement resulting from chloride ingress. In this example, the chloride concentration at the reinforcement is used as a measure of the condition of the structure. When the chloride level reaches some critical value, then corrosion will be initiated and loss of section will result. The objective of an effective maintenance strategy is to increase the service life at minimum cost. For example, routine maintenance such as painting, cleaning and minor cosmetic repairs can be used to slow down the rate of corrosion. Repair or rehabilitation work can be used to restore lost capacity as shown in the figure. This ensures that the structure does not go below the minimum acceptable level of performance - the level below which the structure must not be allowed to reach – as defined by the appropriate technical authority.

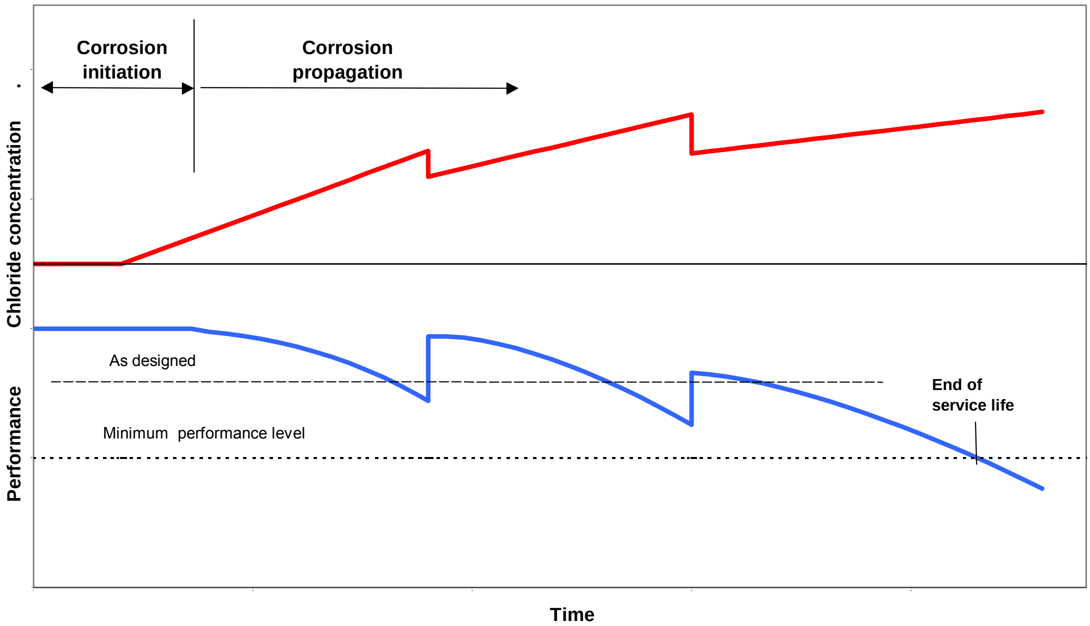



**Figure 15. Corrosion loss and performance as a function of time (BRIME 2001).**

Concerning carbonation, most concrete structures are exposed to the action of CO2 which diffuses into the concrete cover, dissolves in the pore water, and reacts with the hydration compounds, causing a reduction in the pH-value which thus makes corrosion of the steel reinforcement possible (Thiery et al. 2012). This issue is particularly pronounced for cementitious materials with a low portlandite content (CH) since CH is the main supplier of alkaline buffering capacity. Therefore an ordinary concrete (medium to high porosity) made of a binder with a large amount of supplementary cementitious materials is likely to be more sensitive to carbonation.

In case corrosion is initiated, strength loss as a result of corrosion can be due to one or more of the following:

- reduced steel cross-section due to corrosion of the bar;
- reduced concrete cross-section due to cracking or spalling of concrete cover;
- reduced bond between the reinforcement and the concrete due to presence of corrosion products
- change in material properties (strength, modulus) due to corrosion process.

### 3.3.1.2Alkali-silica reaction

Alkali-silica reaction (ASR, also called alkali-aggregate reaction) is a reaction between the hydroxyl ions present in the pore water of concrete and certain forms of silica which may be present in the aggregate. The reaction occurs on the surface of the reactive silica and produces a highly complex alkali silica hydrate in the form of a gel. This gel is expansive in nature and the volume increase can initially be absorbed within the pore structure of the concrete. However, when sufficient quantities of gel are produced, the expansiveness generates internal forces. If these forces are greater than the local confinement can resist, micro-cracking of the aggregate particles and surrounding past matrix will occur.

ASR normally develops slowly and is affected by the temperature and the availability of water. Thus the progress of the reaction is highly variable. Deterioration of concrete only occurs when the following three conditions are met:

- sufficient alkalinity (and consequently high PH value) of the pore water in the concrete, including also external supply of alkalines from de-icing salts or sea water;
- the aggregate contains silica which is susceptible to attack;
- sufficient supply of water.

ASR has been recognised as a potential problem in concrete construction since the 1940s but only came into prominence in relation to UK bridges in 1971, and in relation to French bridges in 1987, when the first cases were discovered. ASR and its structural implications have been described in detail by a number of authors (Hobbs, 1990; Clark, 1989; McLeish, 1990; Larive, 1998) and much work has been carried out on methods of detecting and quantifying the resulting deterioration (Smith and Crook, 1989; IStructE, 1992). Much of the research has been, quite rightly, directed towards the prevention of ASR in new construction by quantifying the risks in terms of materials and environmental. This is equally applicable to existing structures and normally the first step in the diagnosis of ASR derives from an investigation of the aggregate used and its susceptibility to ASR. This section deals with how the strength of a bridge is assessed once ASR has been correctly diagnosed.
World-wide, ASR is recognised as a serious form of deterioration affecting all concrete structures including buildings, bridges and dams. In the UK, some 300 bridges are thought to be affected by ASR, while in France, the number is 400. This has lead to the publication of a number of documents for assessing the strength of ASR affected structures, for example the UK Departmental Standard BD 52/94 (Highways Agency, 1994), British Cement Association (1992) and Godart *et al* (1999).

### 3.3.1.3Freeze-thaw action

Wet concrete exposed to cycles of freezing and thawing is one of the major causes of loss of durability and can cause early loss of strength even in good quality, well placed concrete (it is noted it can be largely avoided with well designed concrete with a sufficient air content).

The type of damage and the susceptibility of concrete to them have been investigated by Fagerlund (1995) and Webster (1995) as part of BRITE/EURAM European Union funded project which examined the residual life of structures subjected to deterioration. Two types of damage were identified:

- internal damage
- surface scaling.

These have different mechanisms and often occur independently of one another. The type of damage depends primarily on whether the concrete surface is exposed to salt laden water.

Internal damage is caused by water freezing inside the concrete. This can occur where water is present in capillary pores in the cement matrix and aggregate, or in voids in the concrete. Damage can be induced in one freeze cycle if the water content is above a critical value. The freezing causes internal cracking, either in the cement paste, or the aggregate particles, or both. The cracks in the heart of the concrete are random but cracks also form parallel to the exposed surface. These are of particular concern as they are also close to, and parallel to, the main reinforcement (since they can accelerate corrosion in the reinforcement). The damage results in loss of cohesion of the concrete, which can reduce compressive and tensile strength as well as the bond between the steel and concrete.

Surface scaling is caused by freezing of the concrete surface in contact with water. Surface scaling is only likely to be a problem when chlorides are present, either from de-icing salts or sea-water. The cement matrix is gradually broken up by this process with the eventual loss of sand and aggregate particles. The main result is that the concrete surface is gradually eroded away which affects the strength and stiffness as well as the appearance and durability. Surface scaling is a progressive problem, with each freeze-thaw cycle producing further loss of material. The extent of scaling is dependent on the severity of the environment, the rat of cooling and the chloride concentration. The main parameter is minimum temperature, and scaling at –20°C is often five times worst than at –10°C. Unlike internal damage, surface scaling is a progressive problem, with each freeze-thaw cycle producing a similar amount of lost material. Scaling can be assumed to be linear with time so that the loss of concrete cover can be estimated.

## 3.3.1.4Scouring of river beds

Scour is an important field of research in civil engineering and includes bridges, coastal erosion, river bank erosion and sediment transport. In addition, it is a topic of ongoing research and makes use of various approaches: hydraulics, sedimentology and geotechnical engineering. Scour depth at the base of structures (like bridge piers) and the rate of local scour and its correlation with influential parameters describing the hydraulic flow, sediment characteristics and structural geometry have being studied by a number of research teams. This focus has given rise to various contributions in journals and international conferences such as the "International Conferences on Scour and Erosion" (ICSE 2002-2012).

Indeed climate change is likely to increase both the probability and magnitude of flood events, which in turn will increase the intensity of scour mechanisms (flash floods or low-water periods).
Current design recommendations are for the most part empirically based in terms of scour risk mitigation, leaving structures insufficiently robust.

For over 30 years, continual improvements have been achieved in monitoring policy and the preventive and corrective maintenance of rail and road structures. The practical principles underlying the monitoring programme have been organised into different actions: periodic detailed inspections of structures, risk analyses and diagnostics, enhanced surveillance based on the in situ implementation of instrumentation, and investigations including bathymetry surveys. A classification of structural sensitivity to the problem of scouring has been partially addressed in the project Smartrail[1].

## 3.3.1.5Fatigue of assembled components

The MIKTI project (MIKTI 2010) describes this degradation phenomenon for welded joints: “Welding is the most widespread technique for assembling components when building steel or composite bridges. Without exception, welding strips constitute the most critical zones from a structural performance perspective. A review of documented deficiencies in the literature indicates that these defects predominantly tend to initiate in the structural joints, in

[1] Smartrail, Smart Maintenance, Analysis and Remediation of Transport Infrastructure, Deliverable 3.1 European Existing Railway Tracks: A Survey Report on typical problems and development of an assessment framework for existing railways

particular on welding strips. The process of welding steel elements actually leads to: modifications in both microstructural and mechanical properties, the introduction of residual stresses, an increase in applied stresses, and the occurrence of welding imperfections. Depending on the set of operating and environmental conditions, one or more of these phenomena may cause part failure through a variety of mechanisms. Within welded joints, fatigue defects are by far the most common kind of defect mechanisms; yet actual failure, albeit a rare occurrence, is indeed the most spectacular mechanism due to the absence of any warning and the extremely serious consequences that very often arise."

### *3.3.2 Criteria used to assess structural performance*

#### 3.3.2.1Safety and load carrying capacity

In the particular case of bridges, the most important factor to consider is providing a safe facility for the road user (PIARC 2004a). For determining the load capacity of a bridge, the majority of countries perform load ratings or use the design load. Load testing can be performed at the completion of the construction project, on suspected bridges or based on inspection results.

#### 3.3.2.2Serviceability and functionality

This criterion includes the adequacy of the infrastructure network to the traffic demand, e.g. the number of lanes provided for the traffic, the adequate clearances for roadway traffic on or under the bridge, navigation clearances for waterway vessels.

#### 3.3.2.3Structural condition

The condition of superstructure and substructure represents a major concern for road assets managers. A numerical rating system is generally used for the assessment of structural condition. Components and elements rated included bridge joints, bearings, waterproofing systems, retaining walls, seismic devices, piers, parapets, embankments, guardrails and pier protection.

### *3.3.3 Non parametric modelling of degradation phenomena*

There is no deterministic law to predict the deterioration of infrastructures as a whole. In this context, this section provides for illustration a non-parametric model to predict the condition of the different elements of the bridge network managed by the French State and already described in sections 3.1 and 3.2.4.

The objective here is to build a transition matrix $P$ directly from the IQOA registered scores (Orcesi & Cremona 2011). The Markov assumption is used stating that the condition of a facility at the inspection *i* depends only on its previous condition at the inspection *i*-1. With this assumption, the present score is the only one which is taken into account to determine the future of the bridge (Bremaud 1999, Madsen et al. 1986). The use of the Markovian assumption can be justified by the particular nature of the bridge stock assessed by the IQOA procedure. The five possible scores given to the bridges correspond to physical states, which are quite different. Indeed there is a gap between the scores 2 and 2E, which highlight equipment failures and scores 3 and 3U, which highlight structural distress. The evolution of a bridge in score 3 will depend more on the distress that has been noticed than on the equipment problems, which happened in the past (Orcesi and Cremona 2011).

The access to the scoring data of approximately 9,000 bridges between 1996 and 2005 makes it possible to determine the probability for 1 m² of bridge to move from one condition rating to another one within one year. Hence, the probability to move from quotation *i* to *j* is the total surface of bridges that were scored *i* at year *p* and *j* at year *p*+1 divided by the total surface of bridges that were in *i* at year *p*, for *p* between 1996 and 2004 (Orcesi & Cremona

2011). This idea is formulated below in a mathematical way, with $n_i$, the number of bridges in *i*, $n_{i\rightarrow j}$, the number of bridges moving from *i* to *j* and $S_i^k$, the surface of bridge *k* scored in *i*.

$$P = \begin{pmatrix} 0.829 & 0.147 & 0.022 & 0.002 & 0.00 \\ 0.017 & 0.916 & 0.058 & 0.009 & 0.00 \\ 0.007 & 0.075 & 0.894 & 0.018 & 0.005 \\ 0.003 & 0.037 & 0.080 & 0.872 & 0.008 \\ 0.014 & 0.028 & 0.112 & 0.085 & 0.761 \end{pmatrix} \text{ with } P(i,j) = \frac{\sum_{k=1}^{n_{i\rightarrow j}} S_{i\rightarrow j}^k}{\sum_{k=1}^{n_i} S_i^k} \quad (1)$$

Results of the Markov chains model associated with this matrix are presented for illustration in Figure 16, which shows the profiles of "quality indices" (see Table 2), and in Figure 17, which shows the total rehabilitation cost of the asset (even if it is not relevant to restore the whole asset in 1 year, the total rehabilitation cost of the bridge stock is used as asset valuation).

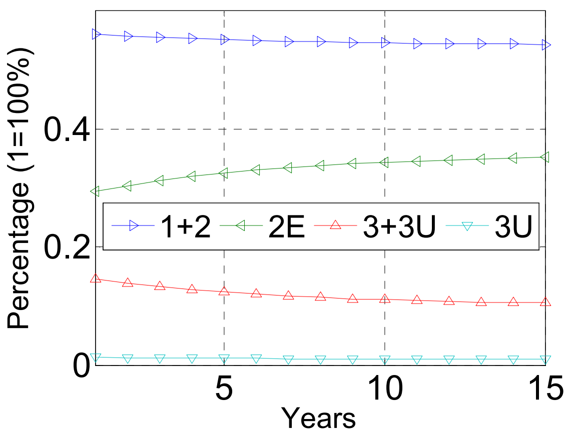



**Figure 16. Development of quality indices (Orcesi and Cremona 2011).**

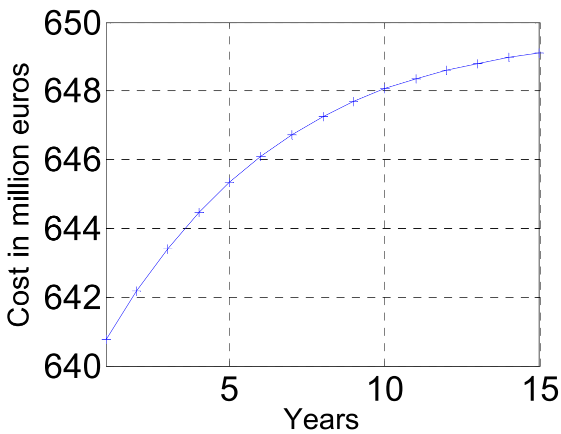



**Figure 17. Evolution of the rehabilitation cost (Orcesi and Cremona 2011).**

## *3.4 Alternative options evaluation*

The decision on whether to repair or replace a bridge has become of great concern to many road authorities. This is due to the high rates of deterioration and demand for increasing load capacity that are occurring on many structures and the subsequent reduction in functionality that has sometimes has occurred.

Concerning bridges, Stratt (2010) reports that most countries do not base their decisions concerning maintenance and repair on the BMS. Denmark uses a prioritization method (Andersen 1990) and Finland uses a repair index (Söderqvist and Veijola 1998). Canada uses a software (PONTIS) to obtain cost optimal strategies. The UK uses cost benefit analysis and France and Germany rely on engineering judgment. Decisions for maintenance work and the selection of options generally hinge on inspections and engineering judgment. Choices made in the UK are dependent on the alternatives available and the cost of traffic delay. For larger, more important projects, a whole life costing approach is used for evaluation (DETR, 1998).

### 3.4.1 BRIME approach

The analysis of the costs of alternative maintenance procedures highlights the need to quantify such factors as the cost of traffic delays, the deterioration rate of bridges, the effective life of repair systems and the time value of money. By doing this it is possible to put forward a programme of maintenance optimised to achieve a set standard condition at minimum long-term cost. Annex A presents the decision criteria methodology introduced in the project BRIME (2001) that helps choose the best repair option that takes into consideration safety, durability, functionality and economy. This annex describes the work undertaken in this project and puts forward a method for decision-making that compares the alternative maintenance options for a deteriorated bridge.

### 3.4.2 IQOA-based optimization approach

Considering the IQOA-based condition assessment presented in section 3.2.4, the Roads Directorate draws up priorities, giving first priority to structures rated 3U, then 3, etc. Nevertheless, maintenance actions on structures scored 2E may be prioritized before structures scored 3 to avoid a rapid evolution of the structural degradation and expensive rehabilitation costs (Orcesi & Cremona 2011). For instance, repainting, replacing waterproofing systems or protecting against external chemical aggression (e.g., deicing salts, chlorides) may be valuable maintenance activities performed on 2E bridges. The Roads Directorate is conscious that this preventive maintenance strategy can be largely improved.

Orcesi & Cremona (2011) presented a methodology to evaluate different maintenance scenarios for the Roads Directorate in France. The objective was not to define the maintenance activities for each bridge, but to provide the Ministry of Transportation witha general approach combining the results of the IQOA scoring program with the financial resources for the management of national bridges. Several prospective scenarios were defined, based on the minimization of the annual maintenance cost. Constraints were introduced for each prospective scenario and the quality indicators, as introduced in the Law of Finance, were evaluated. Figure 18 shows the result of the optimization process when the annual budget Ba was fixed at €50 million, €52 million, and €54 million, respectively (Orcesi & Cremona 2011). It was shown that the first two cases are underestimated budgets since the annual budget needs to be increased during several years to satisfy constraints on the quality indicators (introduced in Table 2), 15 years after having started the corresponding strategy.

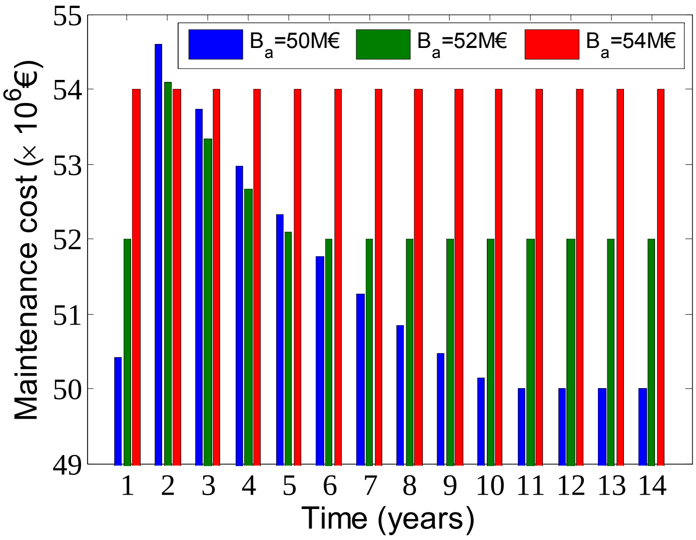



**Figure 18. Development of the rehabilitation cost with several constraints on annual budget (Orcesi and Cremona 2011).**

### 3.4.3 Risk analysis

Risk is a concept which can be defined as a joint measure of the occurrence of a hazard and the consequences induced by its realization (Cremona 2011). It is often traditional to reduce the risk to that of failure probability. This is misused, in the sense that it does not take a lot of factors into account, including the most important: the consequences induced by the hazard or danger.

Hazards can be classified into several categories:

- environmental “exceptional” hazards: earthquake, flood, storm, landslides, soil properties...
- “human activity” hazards: fire, explosion, impact of vehicles, terrorist attack, overloading...
- “initial error” hazards: bad design, wrong design details, poor construction, poor material quality...
- “deterioration” hazards: modification of materials’ properties (corrosion, fatigue)...

A hazard is characterized by its probability of occurrence during a reference period and the intensity of the event. For an existing structure, deterioration hazards resulting from materials’ damage have a probability that increases with time, much faster when the environmental conditions become severe (marine environment, freeze/thaw, ...) and the bridge operation is intense (number of heavy trucks, use of de-icing salts...).

Risk analysis is a powerful tool to achieve certain strategic choices when financial resources of the authority are not expandable. This tool is a technique for identifying, characterizing, quantifying and assessing hazards and their consequences, in order to try to answer the following questions (Cremona 2011):

- Which event may lead to the system’s failure?
- How does it occur?
- What is its level of possibility?
- What will the consequences be?

In the risk analysis methods, several risk categories can be identified:

- the risk of collapse of whole or part of the structure: it is the largest and most serious risk that has human, financial and ecological consequences;
- the risk of loss of serviceability of the infrastructure: the bridge supporting a motorway does not collapse but it cannot be used for a certain duration, which has important consequences on the socio-economic activity of a region;
- the financial risk on the total cost of the project, on its expected life due to construction hazards or on an inability to future needs, ...
- the risk of evolution of the external environment (e.g. new use of an existing motorway as a city ring road).

This analysis can be qualitative or quantitative, but in any case, it must include the following stages:

- identification of accident scenario (or dysfunctioning) leading to equipment failure,
- identification of degradation mechanisms and potential failure modes,
- assessing the consequences (in cost or utility),
- determining the risks,
- defining acceptable risks.

In practice, these stages can be grouped in the four following items (Cremona 2011):

- system analysis: this allows a summarized description of a system's functioning modes and the knowledge of the functions to be ensured;
- qualitative risk analysis: this is a deductive analysis whose results are (i) a basic function analysis of the equipment of the structure, (ii) the identification of errors and non-conformities (bad design or execution, damage, etc.), (iii) the risk qualification presented by each component, (iv) the identification of degradation mechanisms, potential failure modes and possible consequences, (v) a first assessment of additional detailed analyses and investigations which should be envisaged in the framework in a detailed criticality analysis;
- quantitative risk analysis: this completes the qualitative risk analysis by a quantitative approach and rules over the opportunity to carry out detailed investigations by auscultation or calculation, i.e. to proceed to a detailed criticality analysis;
- detailed criticality analysis: this analysis aims to determine means of detecting shortcomings and to evaluate the criticality in a detailed way.

In a risk analysis, the risk can then be assessed qualitatively or quantitatively, for a given failure scenario. For a qualitative risk analysis, the results are often roughly expressed as a risk rating matrix, also known as the consequence matrix (Table 3):

- catastrophic consequences: this relates to the consequences such as significant harm to society (death, permanent handicap), the total destruction of the structure and/or its environment;
- critical consequences: serious consequences but no permanent injuries, partial destruction;
- marginal consequences: consequences such as light injuries, structure rendered unavailable;
- negligible consequences: consequences which do not prevent the structure from use.

The rows of the risk rating matrix represent the occurrence of a hazard, of a threat, or a danger for a given consequence level. A value can be associated with each term in this matrix in a semi-quantitative analysis, to allow setting out some priorities, based on the judgment of experts.

**Table 3. Example of a risk rating matrix.**

| **Risk rating matrix** | Catastrophic | Critical | Marginal | Negligible |
|---|---|---|---|---|
| Likely | 4 | 4 | 4 | 2 |
| Potential | 4 | 4 | 3 | 2 |
| Possible | 4 | 3 | 2 | 1 |
| Unlikely | 3 | 2 | 1 | 1 |

| | |
|---|---|
| 1 | The risk is tolerable : no corrective action necessary |
| 2 | The risk is tolerable : corrective actions may be taken if their cost is moderate and are not to the detriment of other measures |
| 3 | The risk is at the tolerable limit: corrective actions must be sought |
| 4 | The risk is intolerable : many corrective actions must be identified |

### 3.4.4 Real option strategy

The real option strategy was originally developed in the field of finance (Schwartz & Trigeorgis, 2001), (Hull, 2011) and is increasingly used to help managers make decisions in uncertain environments. Using the real option approach ensures that decision makers concentrate, or at least do not neglect the fact that they will in the future obtain more information with respect to the object of their decision and based on this new information they may change their strategy.

The significant advantage of this approach over approaches normally used in infrastructure management is the specific focus on incorporating and valuing flexibility in management systems in determining which ones to follow, i.e. it is not necessary to restrict the management systems that are evaluated to constant ones that are impervious to possible (unlikely) changes in the future demand of traffic or infrastructure behaviour. By using the real option approach analysts are forced to acknowledge that managers have the flexibility to change management systems once new information is obtained, i.e. concentration is given to the possible evolution of a few key factors over time in order to value, and therefore determine, optimal management strategies (Nembhard & Aktan, 2009) (Zhao et al., 2004) (Chiara et al., 2007).

The real options approach recognizes the option value of waiting for better (but never complete) information (Hull, 2011). It exploits an analogy with the theory of options in financial markets, which provides a richer dynamic framework than has been possible with the traditional theory of investment and potentially provides a much richer dynamic framework in which to determine management strategies for road infrastructures. It is considered to be generally applicable when:

1. the investment is partially or completely irreversible, e.g. the costs of executing an intervention on a rail freight corridor are non-recoverable,
2. there is uncertainty over the future rewards from the investment, e.g. the benefits of executing an intervention on an infrastructure depend on the probabilities of the possible futures that can mean greater or smaller benefits (or costs) to the uncertainty due to traffic demand, the uncertainty due to the gradual and sudden deterioration processes of the infrastructure, and the uncertainty in management decisions,
3. there is some leeway about the timing of your investment, e.g. the intervention on the structure can be postponed and during this time more information can be acquired on all mentioned items in bullet point 2.

Using this analogy, a road network manager with an opportunity to execute an intervention is holding an “option” analogous to a financial call option – it has the right but not the obligation to buy an asset (execute an intervention) at some future time of its choosing. When it makes an irreversible investment expenditure, it exercises its option to invest (execute an intervention). It gives up the possibility of waiting for new information to arrive that might affect the desirability or timing of the expenditure (intervention); it cannot disinvest (undo the intervention) should market conditions (the situation) change adversely. This lost option value is an opportunity cost that should be included as part of the cost of the investment (intervention). As a result, the often used net present value rule in infrastructure management, follow the intervention strategy with the lowest total costs, i.e. execute the intervention exactly when suggested by the intervention strategy resulting in the lowest total costs) would be modified. The intervention resulting in the lowest total costs including the *value of flexibility or opportunity value*, should be executed.

### 3.4.5 Multi-criteria analysis methodology

The multi-criteria analysis methodology is based on the most recent developments in multi-criteria optimization under uncertainty. It allows the integration of multiple objectives into the objective function and allows a rational and flexible decision support system, when it is not desired to quantify all impacts using equivalent units. It is now possible to develop such a

methodology due to the recent advances in the fields of computer science and operations research, including the development of genetic algorithms.
This methodology is considered to be particularly applicable when dealing with multiple stakeholders e.g. owner, user, general public, who have multiple objectives, e.g. minimizing $CO_2$ emissions and minimizing intervention costs, and who have to satisfy multiple constraints.
Some advantages of this methodology are:

- it is useful in highlighting the differences in the OMSs when one of more stakeholders are taken into consideration (Orcesi & Cremona, 2010), (Orcesi & Cremona, 2011);
- objectives, such as maximizing connectivity, maximizing traffic throughput (or minimizing loss in system capacity), and maximizing accessibility, can be directly incorporated, without trying to estimate the value of each in terms of a single quantifiable unit. Such information can provide decision-makers with the multi-dimensional perspective sometime required to take into consideration the needs of different stakeholders;
- it is useful in comparing the differences in the optimal strategies determined when the weights of the single objective function are varied.

# 4 Risk management tools considering climate change

Several risks related to climate change have been recently highlighted (CEDR 2012, PIARC 2012b, PIARC 2013) and show how climate change may have significant impacts on society. One main characteristic of climate change is that one is dealing with an uncertain future in which decisions that are obvious under present conditions may become less so if conditions change. Such perspectives justify the use of a risk analysis as introduced in section 3.4.3. Such an analysis should include additional hazards and consequence evaluation in the basic risk rating matrix shown in Table 3.
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) and require 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. A specific part describes infrastructure impacts, specifically on frost/thaw cycles. Increased snow fall (both amount and intensity) raises the risk for avalanches and may yield higher investments in protective installations. Norway and other member countries point out the need to develop landslide and avalanche risk models, better tools for predicting avalanches and avalanche alert systems (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), Thematic Domain Operation and is organised 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 whole of 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 member countries. 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 by the member states of this task group generally not considered as very severe. 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. Besides 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 to mitigate the impact and enhance the adaptive capacity of concrete structures to changing climate. A number of climate change adaptation options were simulated to determine their effectiveness. This included five options that are considered to reduce chloride-induced corrosion including electrochemical chloride extraction, polyurethane sealer, polymer-modified cementious coating, cover replacement and cathodic protection. It also included two options to reduce carbonation-induced corrosion including realkalisation and cover replacement.
Beside 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 change would cause difficulties. 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 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 regard to structuring and establishing priorities for the investments to be made, and in the case of the forecast or announcement of an exceptional event, definition of the scenario to 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 that it can continue to provide 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.

| 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 |

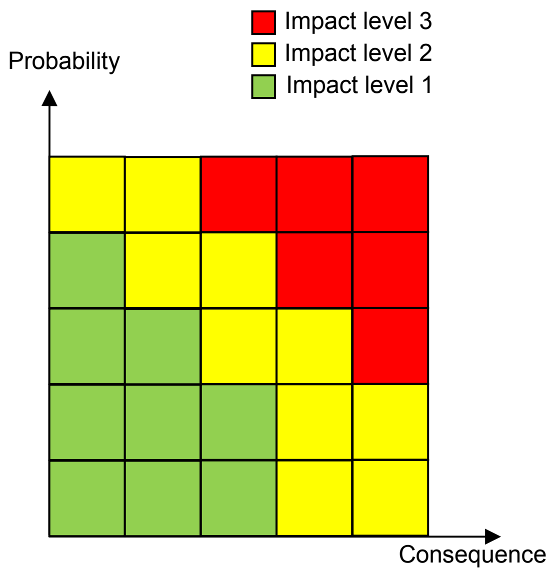



**Figure 19. Risk matrix used to sort the climate change-induced events according to their level of impact (NVF, working group 41. 2008-03-25, working material).**

4. Within the Nordic Road Association (NVF) (www.nvfnorden.org), working group 41, a survey has been carried out regarding what effect climate change would have on the road maintenance. The work was carried out mainly between the years 2004 and 2006 and focused on a risk analysis, i.e. what in the working group's opinion is the probability of a certain event and how big is the consequence. Probability is seen in a national perspective, i.e. the total number of events that occur in the country. Probability can be seen as increased frequency (e.g. storms). Consequences included are costs for road owners and users. The time perspective of the project was from today's climate to expected changes until year 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 disappear 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 risks for unwanted events is measured for each country using colour codes (Figures 19 and 20).

| Effects of climate changes and extreme weather events | Sweden | Norway | Finland | Denmark | Iceland | The Fareo Islands |
|---|---|---|---|---|---|---|
| **Precipitation and water flow changes** | | | | | | |
| Larger landslides and rock falls | | | | | | |
| Road and bridge carried away by water course | | | | | | |

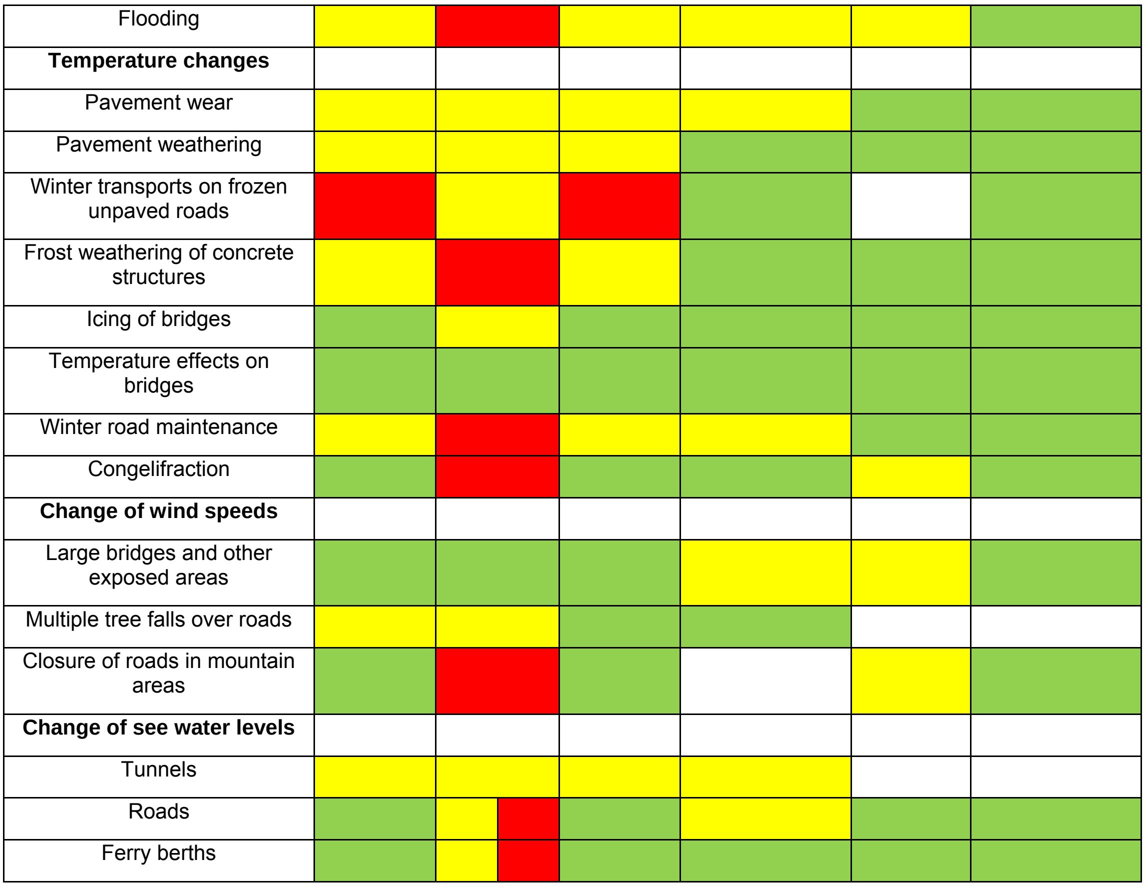



**Figure 20. Risk analysis of impacts of climate change and extreme weather in the Nordic countries (NVF, working group 41. 2008-03-25, working material).**

# 5 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 among which to allocate the funds, asset management challenge is seen as an ongoing and long-term effort.

Dealing with ageing of infrastructures, increase of traffic demand and climate change, several important questions raise 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 impacts of uncertainty in estimating the risk involved in establishing appropriate demand envelopes for various limit events are significant for asset management.

In this context, this report presents basic concepts on asset management, illustrates the different modules of such a framework with examples extracted from previous works and reviews recent studies including climate change effects in the management of road network infrastructures.

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# 9 Annex A - A methodology for evaluating alternative options

The description of decision system for repair/replacement presented in this annex is the one which was proposed in the realm of the European project BRIME (2001).

## 9.1 Theoretical models for repair or replacement

A procedure for helping the engineer to choose the best repair option was developed and is described below. It takes account of safety, durability, functionality and economy, and is based on a global cost analysis that considers all the costs involved in designing, constructing, inspecting, maintaining, repairing, strengthening and demolishing a structure, as well as the road user costs over the service life of the structure. To perform this analysis, a global cost function $C$ is developed as follows:

$$C = C_C + C_I + C_M + C_R + C_F + C_U + C_O - V_S \qquad \text{(A.1)}$$

where $C_C$ = construction costs, $C_I$ = inspection costs, $C_M$ = maintenance costs, $C_R$ = repair costs, $C_F$ = failure costs, $C_U$ = road user costs, $C_O$ = other costs and $V_S$ = salvage value of the bridge.
The objective is to develop a strategy that minimizes $C$ while keeping the lifetime reliability of the structure above a minimum allowable value. To implement an optimum lifetime strategy, the following problem must be solved:

$$\text{Minimize } C \text{ subject to } P_{f,life} \le P^*_{f,life} \qquad \text{(A.2)}$$

where $P^*_{f,life}$ is the maximum acceptable lifetime failure probability (also called lifetime target failure probability).
The repair options considered using this method restore the initial service level (design) of the bridge, but exclude methods that up-grade the structure eg increase its width or load carrying capacity. However, this method could be used to compare options for upgrading a bridge assuming the options being compared give the same level of improved service.

## 9.2 Methodology

The method considers alternative options for the repair or replacement of a deteriorated bridge or a bridge which is functionally inadequate.
The global cost of each alternative is evaluated and the selection of the most suitable repair/replacement option is based on a comparison of the costs. The method allows the choice from a number of different options that depend on numerous factors that can be of a very different nature (i.e. loss of lives, average daily traffic flow etc).
In this method the factors are considered independent or, at least, semi-independent, although that is not always the case (i.e. the traffic volume may be affected by repair work on the bridge as drivers may take an alternative route to avoid being delayed by the repair works).
The possible options take into account the use of different types of repair and the different times when each of the repairs can be implemented during the service life of the bridge. Replacement of the structure is considered as another alternative.
This method is structured in the following phases:
i) identification of the factors

ii) evaluation of the factors
iii) comparison of alternatives and selection of option.

Any cost incurred during the analysis period must be included in the evaluation of the global cost for each option. Its value must be discounted to time $T_0$, common to all options, which is usually the time when the study is made. This is calculated as follows:

$$C_{i,T_0} = C_i \frac{1}{(1+r)^{T_i}} \quad \text{(A.3)}$$

where $r$ is the net discount rate of money, and $C_i$ is the cost incurred during the year $T_i$. In this way all other costs incurred during the analysis period will be discounted to time $T_0$, giving a total cost as follows:

$$C = \sum_{i=1}^{n} C_i \frac{1}{(1+r)^{T_i - T_0}} \quad \text{(A.4)}$$

This cost is then used to compare the various options. Regarding the updating procedure, all the costs incurred during a given year are considered as being incurred at the end of that year.

## 9.3 *Identification of the factors*

The identification of the factors to be taken into account in comparing the repair/replacement alternatives is of great importance, since those aspects not considered will be excluded from the rest of the study.

In fact, the identification phase implies a certain pre-evaluation in which, in a global and approximate way, rough values for the factors are considered; this makes possible to discard effects that will have an insignificant effect on the cost..

On the other hand, the identification of the factors establishes the degree of detail of the study, a general study with a few factors highly aggregated (i.e. which include many different aspects) or a detailed study with many factors highly disaggregated.

The degree of detail that establishes the identification of factors, conditions their evaluation and the comparison of the alternatives later on. It is difficult to evaluate the highly aggregated factors since each of them comprises many variables of a different nature that are hard to analyse as a whole. On the other hand, the highly disaggregated factors are easier to evaluate, although the selection process is more complicated and more entry data are required.

A list that contains the factors that are the most relevant for selecting the best alternative for repair or replacement a typical bridge is given in Table 4. This gives an indication of the factors that should be considered but it should be adapted for each specific bridge. On some occasions it may be necessary add or remove factors or to sub-divide them to provide more detail.

## 9.4 *Evaluation of the factors*

The value of most factors tends to have an objective base and it is usually to make a quantitative evaluation. However it is sometimes difficulties to estimate their value for several reasons: lack of data, accuracy, etc. For example, if a repair option requires the lane width to be reduced by 15%, it would be difficult to estimate the increase in accident rates.

The value of some factors is more subjective and depends on, among other things, social and economic factors, which makes it difficult to quantify their value. Some examples are the

value of lives lost in an accident, the destruction of structures that have a cultural or historical value and the social impact caused by the closure of a bridge.
In cases where a specific factor gives rise to a benefit, it must be included as a negative cost when evaluating the cost of this alternative. For example, if one of the options results in a reduction in journey times.

**Table 4. List of factors relevant for evaluation of alternative options.**

| | |
|---|---|
| $C_I$ | Inspection costs |
| $C_M$ | Maintenance costs |
| $C_R$ | Repair costs |
| $C_{RA}$ | Structural assessment costs |
| $C_{RR}$ | structural repair costs |
| $C_F$ | failure costs |
| $C_U$ | road user costs |
| $C_{UD}$ | traffic delayed costs |
| $C_{UR}$ | traffic re-routed costs |
| $C_{URT}$ | time costs |
| $C_{URO}$ | Vehicle operating costs |
| $C_{URA}$ | Accident costs |
| $V_S$ | salvage value |
| $C_O$ | other costs |

In any case, when a study of alternatives is being carried out, only those factors whose value gives rises to differences between some of them will be considered. Those factors whose value is the same for all alternatives will be disregarded, since they will not affect the comparison of the alternatives.  For example, the cost of the construction of the original bridge may not considered in decision making because it is the same for all the alternatives.
The evaluation of all options must be done for the same analysis period, even if they have different service lives. There are two methods that can be used to take account of differences in service life:

- to assume that shorter service life alternatives will be replaced as many times as necessary to equal the longest expected service life
- to reduce the analysis period to that of the option with the shortest expected service life and to attribute a salvage value to the remaining options

Guidelines for estimating the value of each factor are given in the following sections. Where possible the estimates should be taken from actual data.

### *9.4.1 Inspection costs*

Inspection costs are those incurred during the regular inspections that are carried out as part of the management of bridge structures. They do not include inspections that are carried out as part of an assessment of load carrying capacity undertaken when some form of structural deficiency is suspected.  Also, they do not include the benefits obtained in terms of an increase in the bridge safety reliability as a result of an inspection.  Inspection costs can be divided into *labour costs* and *equipment costs.*
*Labour costs* include all the fees of the personnel that perform the inspection and of those who feed the data into the computer database. *Equipment costs* include depreciation of any

capital equipment used, expendable items and the time spent transporting equipment from one bridge to the next.
There are several methods for calculating bridge inspection costs:
- automatic computation based on the dimensions of the bridge, its location, with standard rates for inspectors and equipment, and a schedule of inspections
- use of regression techniques with data from previous years for similar bridges
- an annual cost.

### 9.4.2 Maintenance costs

Maintenance costs are those involved in preserving a bridge at its design level of service and excludes major structural work They are often uniformly distributed over the life of a bridge, and include only the small repairs that are recommended following periodic inspections.
Maintenance work is proportional to the size and the age of the bridge. As structures age and maintenance costs increase it may become more economic to replace a bridge rather than continue spending on maintenance. Because of the increasing maintenance cost with time, the estimate of these costs is time dependent.
The are several options for estimating these costs:
- an automatic computation in which the yearly maintenance costs of the bridge are a percentage of its construction costs (this can vary with its age)
- regression techniques using data from previous years for the same or similar bridges
- an automatic computation based on the total current maintenance costs for the bridge stock and on the dimensions of the bridge.

The simplest method of predicting annual maintenance costs is to take a fixed percentage of the cost of construction, typical values that have been suggested vary from 1.0% to 2.0%.

### 9.4.3 Repair costs

Repair costs are those for main structural work and include the costs of any structural assessments associated with the repair. For the cost analysis, it is considered that there is no other structural repair work on the bridge.
If replacement of the bridge is one of the alternatives being considered, then the cost of replacement is included as a Repair Cost.
Bridge repair costs can be divided into:

$$C_R = C_{RA} + C_{RR} \tag{A.5}$$

where $C_{RA}$ = *structural assessment costs* and include the fees of the personnel carrying out the inspection, depreciation costs of the equipment used, expendable items and the fees involved in the preliminary structural design of the repair options that were considered, and $C_{RR}$ = *structural repair costs* which include labour, materials, equipment, administration and quality control involved in the application of the repair.
If replacement is an option then $C_{RA}$ would include all the costs derived from the project for the new bridge and the demolition project of the existing bridge. $C_{RR}$ would include construction, supervision and administration costs of both the construction of the new bridge and demolition of the existing bridge.
For a global economic analysis, repair costs can be estimated using data from other repairs on the same type or similar bridges, taking into account the severity and location of the defects, their accessibility, the area of deck to be repaired and the repair method.

### 9.4.4 Failure costs

*Failure costs* $C_F$ include all the costs resulting from any failure that causes a bridge to be closed to traffic, this may range from serious damage to actual collapse. The costs associated with structural failure can be obtained from the probability of failure $P_F$ and the cost of collapse $C_{FF}$. Even though structural failures rarely occur under normal circumstances, these costs should still be included in an economic analysis and they are effectively the insurance costs.

$$C_F = P_f C_{FF} \tag{A.6}$$

In the economic analysis, the estimate of the probability of failure considers, in a simplified way, a linear variation in time during the service life of the bridge. A probability failure path based on degradation mechanisms and the associated reliability index could also be used. Such an approach has the disadvantage that it involves the need to consider in the mathematical modelling a large number of parameters which affect the partial factors for design and assessment and, hence, the acceptable reliability level. Among other parameters, the following would have to be included: size and importance of the structure, degrees of redundancy and ductility, design life, type and modes of failure, frequency of inspection and maintenance, and scope and data acquired from in-situ inspections. The complexity of such an analysis and the difficulty in obtaining reliable data currently limit its use to very important and onerous projects.

*The cost of collapse* can be divided into the costs of bridge replacement, loss of lives, equipment, and architectural, cultural and historical value.

*Bridge replacement costs* include the extra expense involved in replacing a bridge that still has some years of remaining service life. This is done by comparing the cost of replacing a bridge that has failed with the cost of replacing it at the end of its service life. The replacement costs are essentially those of constructing a new bridge and traffic disruption costs during the period of the works.

*Costs arising from loss of lives and equipment* comprise: the value of the lives and injuries to anyone as a result of the failure (or what society is prepared to pay to save them), the value of their vehicles and the disruption to services. The latter include any electricity, water or gas supplies crossing the bridge that were interrupted as a result of the failure. These costs can be estimated from current traffic values and normal insurance values for vehicles and people.

*The architectural, cultural and historical costs* are a way of over-valuing bridges that are especially important from these points of view.

Failure costs can be omitted when comparing a number of options, as they will be similar for each one. If the probability of failure or the cost of collapse for one option is significantly larger than for the remaining options then it is necessary to include failure costs in the comparison.

### 9.4.5 Road user costs

*Road user costs* $C_U$ correspond to the costs attributed to the reduction in the level of service provided as a result of the works being undertaken on the bridge. This may be increased journey times as a result of congestion at the bridge or detours made either as a result of closure of the structure or to avoid the congestion. When doing the analysis it is assumed that other bridges on the same road have no direct effects on these costs. They can be divided into:

$$C_U = C_{UD} + C_{UR} \tag{A.7}$$

where $C_{UD}$ are the costs due to delayed traffic and $C_{UR}$ are the costs due to traffic detours. In order to evaluate road user costs, it is necessary to predict future traffic growth. This can be done in terms of the annual volume of traffic, using a regression analysis or other statistical techniques. The daily distribution of traffic flow over the bridge must also be considered to take account of peaks in the traffic flow e.g. during rush hour periods. This takes account of volume of traffic and the number of heavy vehicles and is based on measurements or on typical distributions.

*The costs due to traffic delays* $C_{UD}$ are those caused by the slowing down of traffic crossing the bridge, especially during rush hours. They are estimated from consideration of the average delay time and hourly value of time for the average user.

$$C_{UD} = ADT_L \cdot C_{H,L} \cdot t_L + ADT_H \cdot C_{H,H} \cdot t_H \tag{A.8}$$

where:

$ADT_L$ : average daily light traffic flow

$ADT_H$ : average daily heavy traffic flow

$t_L$ : additional waiting time, in hours, for light vehicles

$t_H$ : additional waiting time, in hours, for heavy vehicles

$C_{H,L}$ : unit cost per hour for light vehicles

$C_{H,H}$ : unit cost per hour for heavy vehicles.

*The costs due to traffic detours,* $C_{UR}$ are those that arise when traffic is re-routed from one bridge, because of congestion at the bridge or because of it has insufficient structural capacity. They are estimated from consideration of the costs associated with additional travel time $C_{URT}$, additional vehicle running expenditure $C_{URO}$, and the increase in the traffic accident rate $C_{URA}$.

$$C_{UR} = C_{URT} + C_{URO} + C_{URA} \tag{A.9}$$

The costs associated with additional travel time $C_{URT}$ due to traffic detours can be calculated from the following formula:

$$C_{URT} = ADT_L \cdot C_{H,L} \cdot t_L + ADT_H \cdot C_{H,H} \cdot t_H \tag{A.10}$$

The costs associated with additional vehicle running expenditure $C_{URO}$ can be calculated from the following formula:

$$C_{URO} = ADT_L \cdot C_{km,L} \cdot d_L + ADT_H \cdot C_{km,H} \cdot d_H \tag{A.11}$$

where:

$d_L$ : additional length of detour in km for light vehicles.

$d_H$ : additional length of detour in km for heavy vehicles.

$C_{km,L}$ : unit cost per km for light vehicles.

$C_{km,H}$ : unit cost per km for heavy vehicles.

The additional accident costs $C_{URA}$ may be calculated from:

$$C_{URA} = t \cdot ADT \cdot \sum_i r_i \cdot c_i \tag{A.12}$$

where

$ADT$ : average daily traffic flow.

$t$ : time when the increment of the accident rate occurs.

$r_i$ : increment of the accident rate for type *i* accidents.

$c_i$ : the cost of type $i$ accident.

$i$ : type of accident. These are classified in three groups: fatal accidents, injuries caused by accidents and damage to materials.

Programmes have been developed in several countries for evaluating road user costs under different circumstances. For example, in the United Kingdom a computer programme called QUADRO (QUeues And Delays at ROadworks) provides a method for assessing the cost imposed on road users while road works are being carried out. These include, road user delays (value of time), vehicle operating costs and accident costs.

### 9.4.6 Salvage value

The salvage value of a bridge is its value at the end of the analysis period. An estimate of the salvage value must be made when the analysis period is shorter than the service life of the structure. It can be estimated by assuming that its value is zero at the end of its service life and it is equal to the cost of construction when the bridge is put into service. The value at some intermediate point may then be interpolated from these two extremes.

### 9.4.7 Other costs

Other costs (Co), cover other aspects of a different nature that can give rise to additional costs for some alternatives and whose influence can be important in some cases. Some examples are given below:

- restrictions in the use of the structure eg reductions in vertical clearance, reductions in lane widths, lane closures, removal of hard shoulder from service,..
- influence of the proposed option on other users eg pedestrians and cyclists,
- absence of alternative routes for light and/or heavy traffic that require special measures, eg, construction of a temporary bridge,
- for bridges used by public transport eg buses, coaches and school transport, the absence of alternative transport over the same route eg rail,
- influence of the repair works on other modes of transport (railway, high speed, etc) that may cause traffic disruption on them, limitations on the repair works i.e. working hours, night time working hours, etc.
- economic affect on local businesses eg disruption to traffic crossing a bridge may affect shops and local industries in the vicinity of the structure,
- environmental impact of the works on the local community eg noise, dust and contaminants,
- loss or reduction of historic, patrimonial, aesthetic, religious and traditional values of the bridge at all levels i.e. national, regional and local,
- additional expenses incurred during the works i.e. staff, boards, beacons and other signalling,
- convenience of a given alternative from the point of view of the use of available equipment, stocked materials, similar actions in nearby places, etc.

## 9.5 Comparison of the alternatives

As stated above, the selection of alternatives is based on minimising the total cost over the analysis period.

In the model described above, the repair index ($RI$) is used to determine the relative costs of each option, this is usually done using the do nothing option as the reference; the smaller the coefficient for a particular option, the better investment. In the calculation of $RI$, the inspection costs $C_I$, the maintenance costs $C_M$, the repair costs $C_R$, the failure costs $C_F$, the road user costs $C_U$, other costs $C_O$ and the salvage value $V_S$ are considered. For each option the $RI$ may be quantified by:

$$RI = \frac{(C_I + C_M + C_R + C_F + C_U + C_O - V_S)_{\mathrm{Re}\,pair\ \text{or replacement}}}{(C_I + C_M + C_R + C_F + C_U + C_O - V_S)_{No\ action\ or\ reference\ alternative}} \tag{A.13}$$

The economic analysis considers a certain number of parameters whose accuracy cannot always be guaranteed: values of discount rates, inspection costs, maintenance costs, probability of structural collapse, evolution of traffic, etc. It is therefore useful to know the sensitivity of final results to each parameter in order to try to estimate more carefully those that have the most influence.

The $RI$ coefficient may be used at different levels of actions, but its principal goal is to compare and select the best alternative for the repair or replacement for a bridge. On the other hand, the method allows the global cost of each alternative to be calculated and the alternatives to be ranked in terms of cost. It also can be used to evaluate the differences in cost if any action is deferred and for this to be included as one of the options. This method can provide useful information and enable comparison of different actions on a range of bridges on the network, on the basis of a consistent set of criteria.