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Decision-making system based on risk analysis for sustainable management of civil engineering infrastructure

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ABSTRACT. Civil infrastructure is assuming an ever more prominent role in society and strongly contributes to its sustainable development. Faced with multiple stakes, civil infrastructure owners have a responsibility to guarantee operations throughout the lifespan of an ageing and varied asset base, whilst ensuring optimal safety and availability conditions at reasonable cost. It is therefore essential to optimize available resources by focusing them in areas where they will have the greatest effect. To achieve these objectives, a sustainable risk-based management system for civil infrastructure is presented. Its purpose is to supply owners with an overall view of the performance levels of their assets in a “risk” based context, and a long-term forecast of maintenance costs based on a multiple-stake comparison. This approach, and its results, is illustrated by a case study relating to a port.

KEY WORDS: sustainable management, risk control, forecast, ageing, decision, multi-annual programming, maintenance, civil engineering infrastructures.

1. Introduction

Under the pressure of the current economic climate, the operational life span of civil infrastructure assets is often prolonged, sometimes in worse environmental conditions than anticipated during design. In such situations, maintenance costs increase and can reach significant levels. In order to optimize available resources by focusing them in areas where they have the greatest effect, two important questions are raised: “What are the risks associated with current operational assets?”, and “How can these risks be managed?”. Owners are thus faced with ensuring a delicate balance between these two aspects in order to maintain acceptable performance levels, a problem to which a risk-based approach is particularly well adapted.

In the current article, a sustainable risk-based management system is presented, based on the following three steps: (1) identification of hazards and failure modes for each asset family; (2) risk assessment for each asset; (3) development of long-term maintenance programs based on risk prioritization.

The purpose of this management system is to assist owners in managing and controlling the risks associated with ageing infrastructure, whilst optimizing allocated resources. This approach, as well as the anticipated benefits, is illustrated by a case study relating to a port.

2. Objectives of the sustainable management system

A maintenance master plan is an important tool for civil infrastructure owners, and one that is all the more important when faced with an ageing asset base, often accompanied by budgetary restrictions. The principal objective is therefore to identify and justify the most cost-effective maintenance solutions.

To this end, the proposed management system allows the development of a maintenance master plan tailored to the performance requirements of the considered asset base. In order to achieve this, the plan must be based on

predictions of the assets' future performance levels, amongst other associated issues. The plan will ultimately result in short-, medium- and long-term maintenance programs for the asset base, as well as a costed and prioritized list of associated maintenance actions (surveillance, current maintenance and repairs). The benefits of this approach for the engineer are as follows: a formal maintenance policy with a well-defined methodological framework; an identification of hazards and failure modes for each asset; a hierarchy of maintenance actions based on technical and economic criteria; a report detailing the actions to be undertaken and the consequences if not undertaken. The benefits for decision-makers are as follows: an overall vision of the risks affecting the asset base and maintenance costs for treating risks that are deemed to be unacceptable; an assessment of the main stakes facing the asset base; the use of performance monitors as a quality assurance measure.

3. Management system for the elaboration and implementation of a maintenance master plan for a large port

3.1. Global stakes associated with port activities

Port activities (commercial, fishing, sailing, military) are of considerable economic importance for nations and for the defence of their vital interests. Commercial ports play an essential role in the international exchange of goods, not only for the import and export of basic products for economy (crude oil, petrol products, natural gas, minerals, coal, fertilizers, cereals, etc.), but also for the exchange of high-value manufactured products (containerized goods). At present, three-quarters of the world's commerce is transported by sea transport. Today, maritime shipping, in constant growth, remains the most economic method for freight with a transport cost of between 0.3 and 1.6% of the final product cost. Moreover, from an environmental and sustainable development point of view, it remains the most ecological mean of transport.

Military ports, constructed in strategic locations, have an important role in ensuring the reliability and speed that are crucial to successful operations. As an example, French and British military ports play a major role in the defence of Europe's vital political interests at sea. France and Great Britain are the only two member state of the European Union to operate military navies with global reach.

3.2. Role and functional breakdown of the port

A port is a natural or artificial shelter for cargo ships and/or boats that provided the necessary infrastructure for their construction, maintenance, demolition, docking, replenishment of supplies, and transport operations (loading and unloading of cargo and passengers).

From an economic point of view, a port is a transport hub for cargo ships and/or boats that ensures the continuity of maritime, river and terrestrial (road or railway) transport routes. As well as acting as a junction between different transport networks, ports can provide another function; that of encouraging the growth of factories and industries in nearby areas. This is because there is a real economic interest in processing goods that have been imported or exported by maritime and river transport networks, and in undertaking commercial operations, close to transport hubs, thus limiting the need for terrestrial transportation.

Several structures and their different functions are shown below (cf. Figure 1).



Dike with slope protection constructed from concrete shielding (Protection against ocean swells)



Reinforced concrete quay (Docking)



Mobile bridge (Crossing obstacles)



Dry dock (Construction and repair of ships)

Figure 1. Illustration of various harbour assets.

In order to function effectively, a port must have facilities geared towards both land and sea operations (Boéro *et al.*, 2009a, 2009b). If the position of a port in the transport chain is to be consolidated, these facilities must provide optimal speed, security and reliability, all at reasonable cost (cf. Figure 2).

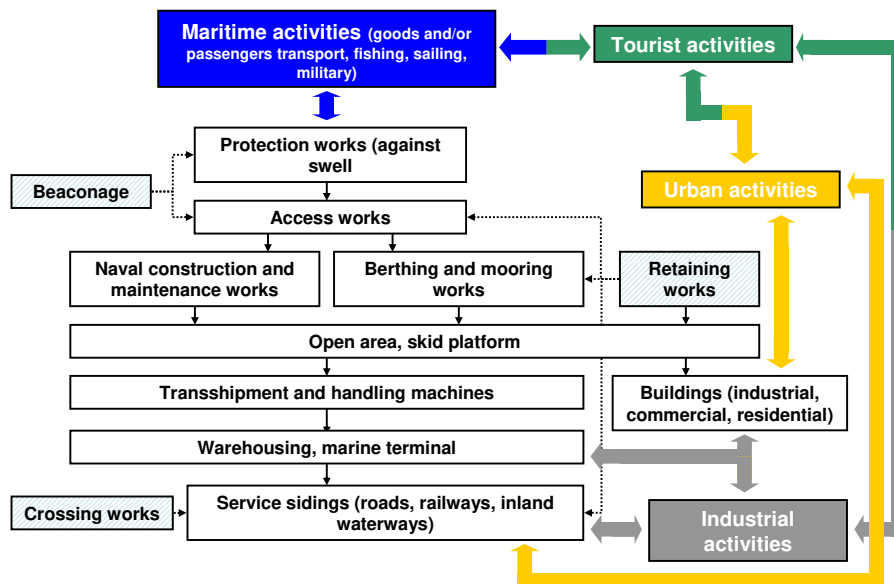


Figure 2. Activities and interactions between functional domains in the “port” system (Boéro *et al.*, 2008).

It is important to recognize that assets associated with so-called secondary activities (industry, tourism, urban planning, services, etc.) are an integral part of the “port” system, irrespective of whether or not they contribute to primary (maritime) activities.

The asset base should be divided into functional domains for it to be incorporated into the management system. A functional domain is a set of similar assets that perform the same general function. The interaction between the different functional domains that make up the “port” system, as well as their role in primary and secondary activities, is presented in figure 2.

A “port” system can only perform well if all its functional domains perform well too. In the case of a merchant shipping port:

- a ship entering port must be able to reach its dock quickly and easily, which often requires it to navigate through several basins, sluice gates and locks;
- goods must be able to be rapidly transhipped or, if necessary, stored for long periods of time before being forwarded on, all at minimal cost. Finally, they must be able to be transported by land (roads, railways) and/or interior waterways from the port to exterior transport networks.

A quantitative analysis of the French port asset base was carried out as part of the GEROM project (Risk-Management of Marine and River Ports), led by a partnership between the risk-management consultancy Oxand and the Institute in Civil and Mechanical Engineering. The following issues were highlighted:

– many different construction techniques have been used, an indication of engineering ingenuity when faced with challenging marine environments, but also of the variation and complexity in mechanical behaviour of marine structures.

– large age variations between assets, with the most recently constructed ones having significant importance for local, national, even European economic development.

The non-uniformity of the asset base puts owners in a delicate position with regards to maintaining acceptable performance levels. A risk management approach is well adapted to this kind of problem (Billard *et al.*, 2007; Boéro *et al.*, 2009c).

3.3. Uses and specific characteristics of the management system

By taking into account the objectives of the maintenance master plan, and by understanding the stakes and role of marine facilities, a set of requirements for the management system was developed to guarantee the use of the notion of risk as a strong tool for making decisions support for maintenance of asset base:

- it must be applicable to any asset, be able to take into account specific issues and must be capable of making comparisons between assets;
- it must be able to integrate the experience feedback (records of past maintenance works, inspection results, etc.) in order to predict ageing and elaborate the maintenance master plan;
- it must take all possible failure modes into account, be able to provide a level of detail that can be adjusted according to the owners needs and be consistent with the maintenance strategy;
- it must take all appropriate stakes into account (human, economic, environmental, financial, social, political, etc.) and be accessible to both technical and management teams.

3.4. Process of the risk-based decision-making system

The development of a maintenance master plan for ports, using the risk management system presented in this article, is based on three main stages, described below (cf. Figure 3):

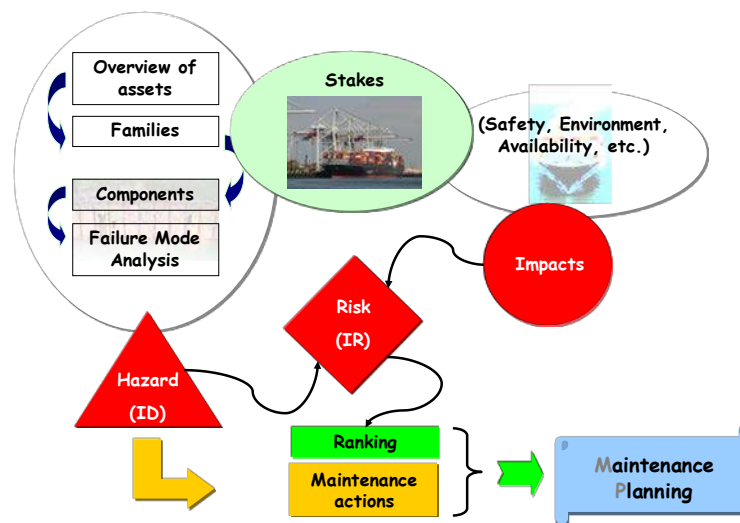


Figure 3. Process of the risk-based decision-making system.

3.4.1. Stage 0: Preliminary analysis

The preliminary stage consists of establishing an asset inventory; then grouping the assets into families based on their main functions (cf. Figure 2) and sub-families based on purely technical criteria (construction techniques, material, etc.). The purpose of this stage is to gain a good understanding of the stakes affecting the assets, and to understand the owner’s needs, for example the levels of maintenance that define how well an asset is performing. For an owner faced with the problem of maintaining port infrastructure, the stakes often include the required availability of assets, the extent to which they can safely be used, and respect for the environment.

3.4.2. Stage 1: Failure modes analysis and definition of the maintenance actions

A functional analysis is carried out in order to identify the generic structural components in each asset family, as well as any specific issues that are important in a small number of cases (for example, structures that have been repaired or reinforced). The functional analysis for the “steel sheet pile seawall” sub-family is shown in figure 4.

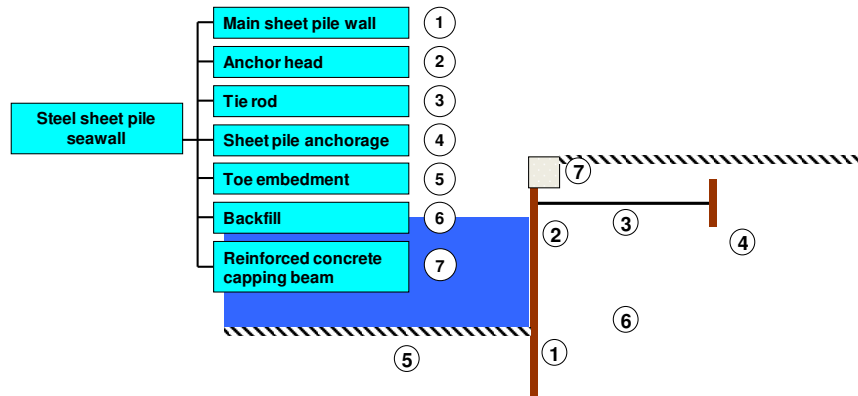


Figure 4. Functional analysis of a steel sheet pile seawall.

An analysis of the hazards (or failure modes) affecting each of the previously identified structural components is then carried out. For example, in the “steel sheet pile seawall” sub-family, one of the possible hazards for the sheet pile component is “loss of mechanical resistance due to steel corrosion in marine environment”.

Finally, a hazard index (frequency level) is assigned to each of the identified hazards. Hazard indices are defined by feedback capitalized within notation systems, which are in turn obtained from computer simulation software, for example the SIMEO™ Consulting program for modelling the effects of ageing in reinforced concrete structures (Crouigneau *et al.*, 2008). If the problem proves to be too complex to model in this way, expert judgements are sought to evaluate the hazard index in a transparent and contradictory way.

The choice of maintenance actions is then made per asset family or sub-family, and consists of developing a catalogue of maintenance actions by identifying all the possible interventions that could be used to treat a problem: from “no action” to “renewal”, with indications of the unitary cost and intervention timescale. These actions can be curative, preventative or predictive. Each hazard for each asset is then assigned a maintenance action, based on its hazard index.

3.4.3. Stage 2: Risk analysis

Finally, each hazard for each asset is given severity ratings for each stake (consequence). When coupled with the hazard index, this allows a risk index to be established for each stake. Therefore, all the hazards associated with a particular asset are assigned a hazard index, and a set of risk indices corresponding to each stake. The two stakes that are generally used for ports are safety of goods and people and availability. For the latter, severity ratings can be obtained by considering the potential loss of profit that would be incurred if the asset were to be put out of service for any period of time due to a particular hazard.

3.4.4. Stage 3: Elaboration of long-term maintenance plans

This stage consists of establishing a risk hierarchy per stake, using either the risk indices (IR) calculated in stage 2, or by means of a global risk index, which makes no distinction between stakes once these have been assigned monetary values. It is at this stage that the owners are consulted to determine an acceptable risk threshold. Then, only actions treating risks that are considered unacceptable are considered.

The objective of this phase is to establish a set of coherent and realistic maintenance actions at the level of individual assets, asset families and eventually the entire asset base, whilst taking into account any specific intervention constraints associated with the assets.

Finally, a risk hierarchy and a long-term maintenance plan are established based on risk indices and taking into account operating constraints (available annual budget, human resources, etc.). Long-term planning of maintenance actions requires time to be taken into account, thus the risk indices for each hazard are evaluated at regular intervals throughout the time period under consideration. Given that the risk index is determined from the hazard index and the indication of severity, it is necessary to define the time evolution of these two indices (cf. Figure 5).

The time evolution of the risk indices obtained for a given hazard is then combined with the acceptable risk threshold defined in stage 3 to obtain limiting timescales for each hazard, during which an intervention must occur.

Planning may also be based on an economic analysis: several different maintenance scenarios are simulated in order to identify the most efficient ones in terms of costs and global risk reduction.

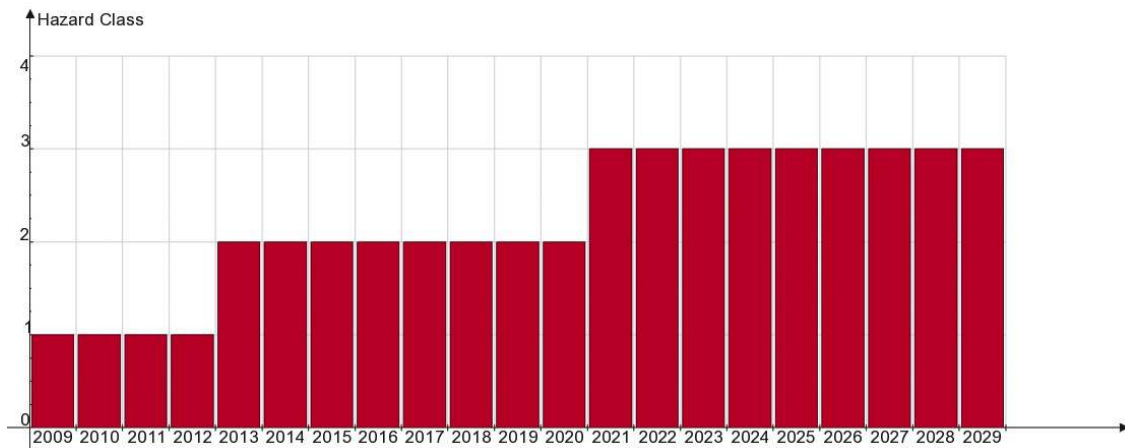


Figure 5. Time evolution of the hazard index throughout the lifespan of the component studied, consistent with the time-based objectives of the maintenance master plan.

3.5. Decision-making support for owners

The results of the management system are therefore:

- an inventory of the asset base, a functional analysis of each asset family, hazard grids for each asset and/or the entire complex;
- risk grids for each asset based on its risk index (classification per stake or a unique classification if a relationship was established between different stakes). This classification allows the identification of critical assets that require suitable treatment. An example of a risk grid for the “availability” stake is shown in figure 6.

AVAILABILITY	1 : < 10 TED	2 : 10 to 1 000 TED	3 : 1001 to 100 000 TED	4 : > 100 000 TED
6 : Almost certain	1 15	3 3 11	16 20	5 24
5 : Very probable Already observed on spot	10 3 11	10 16	16 19	12 23
4 : Probable	4 7	6 2 12	21 5 18	9 1 22
3 : Improbable Never observed, but worried	19 31 4	4 4 8	7 10 13	7 6 21
2 : Very improbable Never observed	5 8 2	9 11 5	35 41 9	27 29 14
1 : In agreement with the standards	7 16 1	3	63 102 8	40 64 10

Figure 6. Example of a risk grid associated with the “availability” stake, before and after interventions for a given year.

The risk index for the “availability” stake is defined by the intersection between the loss of profit (columns) and the annual risk probability level (rows) in the risk grid. This probability is directly associated with the hazard index. The loss of profit is expressed in TED (Diverse Equivalent Tonnage) in order to establish an equivalence in terms of added value between the different types of goods that pass in transit through port complexes: crude oil, petroleum products, natural gas, minerals, coal, fertilizer, cereals, etc. The numbers in the far right of each grid box, ranging from 1 (least critical) to 24 (most critical) allow the relative criticality of risks to be determined, based on their position in the grid. The circled figures at the left and right of each box also correspond to the different risk indices (1 to 24), but represent the number of risks before and after interventions (summary visits, detailed inspections, repairs, etc.) have been carried out, respectively. In the example presented, the acceptable risk threshold was fixed at 10. It should be remembered that only risks with a criticality rating above the acceptability threshold are considered. The grid allows the time evolution of the criticality rating to be monitored and therefore provides a measure of how effective the adopted maintenance policy is. The grid is also used to support decision-making, which in turn provides a basis for the maintenance program to be carried out, and their associated timescales (remembering that interventions will only be considered for risks which are or will be unacceptable), specific details for each recommended intervention (technical, cost, timescale, etc.) as well as short-, medium- and long-term financial costs. As an example, the repartition of the annual maintenance budget per type of intervention for a given timescale is shown in figure 7.

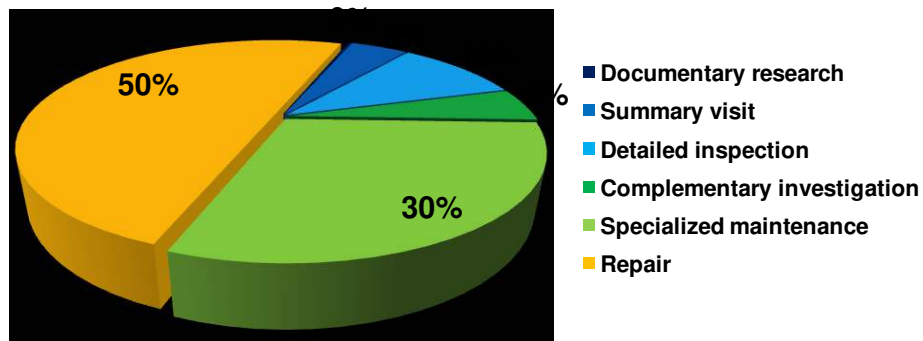


Figure 7. Example of the annual budget breakdown per type of intervention for a given year.

4. Conclusion

Maintenance managers are facing strong budgetary constraints and consequently, most of the time, are engaged in curative maintenance programs, in which ageing structures are often repaired in crisis situations or just before. The establishment of an overall vision of the performance and the risks associated with the asset base are still not sufficiently widespread. However, the minimization of disruption to business and the optimization of maintenance budgets are major stakes related to civil infrastructure.

The risk-based method for developing maintenance master plans that has been presented in this article provides owners with decision-making tools for optimizing the maintenance of their asset base. This approach and the feedback integrated in the software SIMEO™ Maintenance achieves the following results: a formal maintenance policy with a well-defined methodological framework; an overall vision of the risks affecting the asset base and therefore also an overall vision of the performance of the asset base; a means of predicting and allocating the short-, medium- and long-term maintenance budget in a coherent way, based on a multiple-stake comparison; an efficient means of defining and organizing resources.

The applicability of risk management systems is not limited to the sustainable management of civil infrastructure. Apart from certain specific aspects of civil engineering, notably the lifespan of assets, the principles of the method can be applied not only to other types of industrial assets, but also to various processes and projects.

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