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Transportation Research Procedia 14 (2016) 4060 – 4069

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

Towards a comprehensive asset integrity management (AIM) approach for European infrastructures

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Abstract

Transport infrastructure is the backbone of national economies, providing connections for people and goods, access to jobs and services, and enabling trade and economic growth. It is of paramount importance to preserve, maintain and upgrade the infrastructure network so that to sustain the economic growth and an intelligent mobility. Asset Integrity Management (AIM) approaches will therefore represent key tools for facing the infrastructure maintenance issue and for tackling the ageing that characterize already existing assets.
This paper, starting from analyzing the current state of the art solutions in assets management (Enevoldsen, I., 2008), proposes a comprehensive AIM approach that aims at replacing current time-based approaches with a performance-based approach that can systematically take into account the dynamic nature of the transport network. This means moving from a deterministic to a probabilistic approach in design, rehabilitation and retrofitting of infrastructures for increasing life-time and reducing maintenance costs. Such approach therefore laid the basis of secure sustainable impact since by improving awareness and reducing uncertainties, it might allow achieving an optimal balance among available resources and planning of investments.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

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Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.503

Keywords: Performance-based design; asset integrity management; self-monitoring, decision support

1. Introduction

Transport infrastructure is much more than asphalt, concrete or steel; it is the backbone of national economies, providing connections for people and goods, access to jobs and services, and enabling trade and economic growth (International Transport Forum 2013). This highlights the role of infrastructures as one of the main pillars of European society. However, infrastructures suffer from ageing (as they are approaching the end-of-life) and increased fatigue issues (vehicle weights and traffic increased over time). Bridges (Sustainable Bridges) and tunnels are relevant infrastructures suffering of these problems (Vienna Consulting Engineers). Although positive trends (e.g. improvements) in the health status of infrastructures (bridges and tunnels in particular) have been demonstrated across Europe, for instance in Italy, Spain and in Germany (see the Condition Index (CI) in Figure 1) Investments on infrastructures have been dramatically decreases in the same time frame (e.g. 2001-2011). Given the fact that bridges constitute the 90% of the total assets of all engineering structures in Germany (valued at approx. 50B€) and that Italian tunnels represent 70% of the whole European tunnel network, the situation requires a long-term and effective strategy.

Nowadays Germany estimates a budget allocation of respectively 300-500M€ (Federal Ministry of Transport in Germany) for maintenance of more than 40000 bridges/tunnels, and in Italy, Autostrade per l'Italia estimates an allocation of more than 40M€ (Factbook) a year for more than 4000 bridges and tunnels. These investments are to be used in the most effective way to guarantee a correct and lasting maintenance to assure the survival and upgrade of the infrastructure. However, the efficiency of such investments depends on the type of inspections and interventions that are planned/actuated on a time-basis, which could result in extra-costs. Moreover, it may be envisaged that due to the actual economic situation, less financial resources would be available in the future: in order to properly handle the ageing infrastructures, a different management approach is needed. This, combined with the fact that the costs of new European infrastructures is costly more than maintaining the existing network, brings to the point that Europe can have an healthy, available and usable transport infrastructures network, mainly by preserving and prolonging the life-time of the existing network. Indeed, upgrading the existing infrastructure is in many cases the cheapest way to enhance the overall performance of the transport system (A sustainable future for transport, 2009).

In this scenario, visual inspections can be significantly improved using non-destructive test methods or Structural Health Monitoring (SHM) techniques. Continuous data allows a better assessment of a structure performance and an improved prediction of its durability and remaining life time. Data can be then used to trigger inspection autonomously and based on the current performance. More precise data will make possible a recalculation of structures capacity and a compliance with guidelines (Federal Ministry of Transport in Germany) that, validated in pioneering countries like Germany, may become standards in Europe.

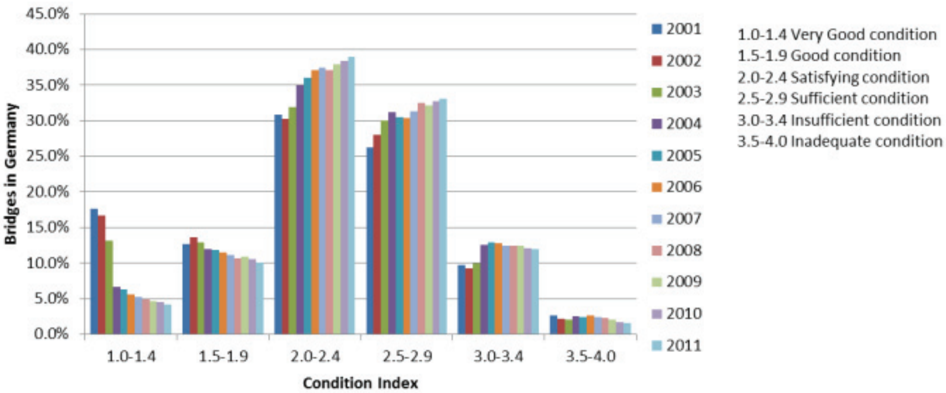

Fig. 1. Example of Condition Index for Bridges in Germany (Federal Ministry of Transport in Germany).

2. Asset Integrity Management of Transport Infrastructures

Within this context, it is clear the need to move from current time-based approach in Asset Integrity Management (AIM) to performance-based approach that can systematically take into account the dynamic nature of the transport network to be used in the management (design, repair, etc.) and maintenance planning of infrastructures. This means moving from a deterministic to a probabilistic approach in design, rehabilitation and retrofitting of infrastructures to increase their life-time and reduce maintenance costs, taking the “risk” element or the “risk-based analysis” as primary driver. To achieve this overall objective, an analysis of the current solutions available for AIM is needed in order to understand where the progress beyond current State of the Art (SoA) are mainly required and therefore focus the research activities and investments in a certain direction. The following table reports the results of this analysis by comparing the features and characteristics provided by standards and commercially available AIM system vs. the requirements or better the desiderata from the industrial sector (Infrastructure Assets Code Consultation Document) and the stakeholders involved in the infrastructure sector. Most of commercially available AIM systems mainly rely on the management of physical assets permitting their ability to perform required functions, basin the assessment of future asset integrity on the past and without the introduction of mitigation measures that account for the adoption of risk-based solutions.

Among the others, the following AIM systems have been considered for comparison: Intertek solution for civil infrastructure (taken as reference for specific and advanced AIM tools); SAP solution (taken as worldwide industrial reference of AIM) and finally the AIM tool for structures by Bureau Veritas (taken as reference for tools provided by certifying bodies). Although these tools are commercial ones, in most of the cases, they do not include all industrial inputs, do not have risk-based approach and finally do need customizations according to the type of infrastructure selected. Therefore there is the need for solutions that account for the specific dynamism of the transport infrastructures, there is the need for the development of additional services to ensure network continuity minimizing maintenance and optimizing repairs, and the need for the use of predictive analytical models for the assessment of the future asset performance.

Table 1. Features and Characteristics of current AIM solutions vs. Industrial Requirements.

Features	Industrial Requirements	Intertek	SAP	Bureau Veritas
Life extension & design update	Yes	Yes		
Regulatory compliance	Yes	Yes	Yes	Yes
Certifications & Verifications	Yes	Yes	Yes	
Risk Based Analysis	Yes	Yes	Yes	Yes
Risk Based Design	Yes			
Financial Analysis	Yes	Yes	Yes	
Probabilistic loss analysis & Risk transfer	Yes			
Business continuity	Preferred	Yes	Yes	Yes

3. Proposed Concept

Within this framework, the primary objective of any future advanced AIM solution should be to keep an asset in a fit-for-service condition while extending its remaining life in the most reliable, safe, and cost-effective way. This is achieved by combining Design, Engineering and Operational Integrity. The Oil & Gas sector for instance has implemented this approach since many years. However, the transfer of this approach to the infrastructure sector is not so straightforward. Indeed, while the Oil & Gas sector can be considered quasi-static (processes involved are subjected to slow-varying constraints), the world of transport networks is highly dynamic during its life-time (boundary conditions can vary). To make this possible and effective, performance-based methods need to be accounted for, as they allow characterizing all the variables involved in system design as probabilistic variables, evolving according to a specified Probability Density Functions (PDFs). This means moving from a deterministic approach (allowable stress) to a probabilistic approach in the design, repair and maintenance of the infrastructure as depicted in Figure 2. An investigation of the feasibility of this approach has been already proposed by Neumann T., 2012.

Core of the analysis is the construction of the probabilistic evaluation that an encountered load (L) may exceed the ability of the structure (resistance R) to carry that load, represented by the overlapping portion of the PDF curves. The probability that L exceed R represents the failure state of the system or P_{fail}; this can be preliminary estimated via the calculation of a reliability index (ϕ) or in a fully probabilistic approach (e.g. Montecarlo simulations) where the solution is found through iteratively random generated simulations to determine those which fall into the limit state domain. Inspections and monitoring can provide in-service data (at both micro and macro scale level) and statistical information that help in accurately estimating, over the life-time of the infrastructure, the PDF of R and L and in predicting their future evolution. The main advantages in adopting such approach will be:

- Characterization of the variables/parameters involved in the calculation (for design and repair) of a structural system as probabilistic variables/parameters, evolving according to specified PDFs
- Reduction of uncertainty and variability of design across infrastructure lifetime (Life Cycle Approach)
- Optimization of repair design to deliver improved solutions
- Adoption of condition-based and predictive maintenance logics by leveraging on the use of data from inspections and monitoring in probabilistic analyses
- More precise estimation of failure models (and their effects) of a structural system

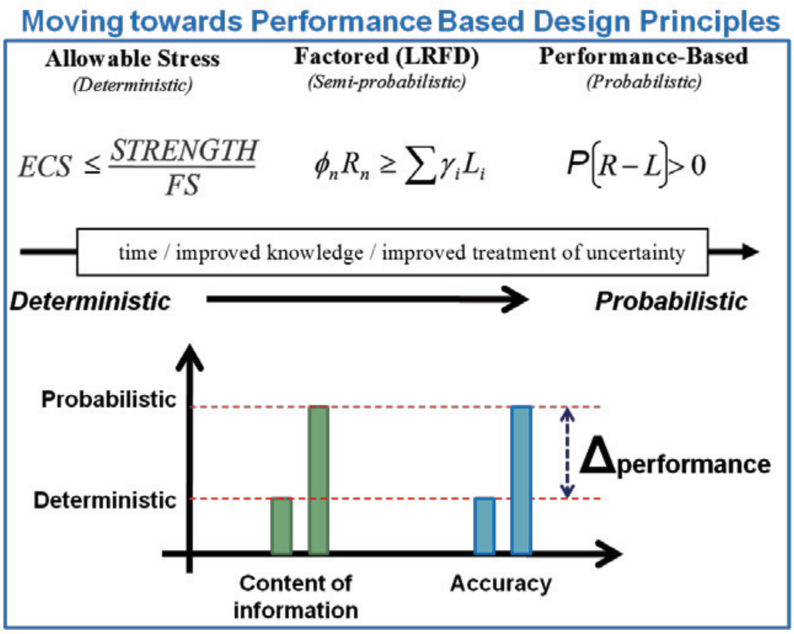

Fig. 2. Overall concept: moving from deterministic to performance based design principles.

This transition is clearly shown in the Figure 3, moving from the Step 0 (current situation) to a probabilistic approach (Step1) as short term solution up to a predictive approach in AIM as a long-term perspective. Changes are needed and there are opportunistic if we want to keep the same or even higher performance and availability of the transport network in the future considering an ageing infrastructure and an increase in demand.

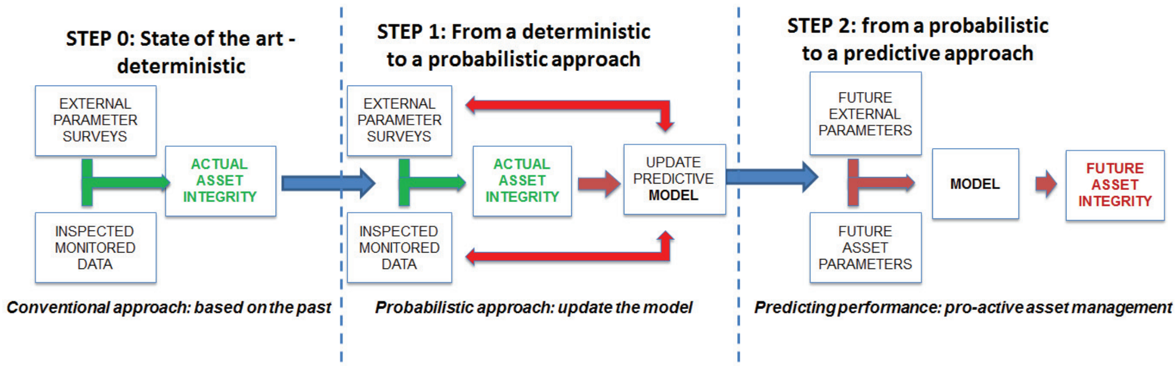

Fig. 3. Transition from a conventional to an advanced futuristic approach.

For instance, when it comes to "repair design", it is of paramount importance to achieve a better understanding of degradation and ageing processes and to reduce disruption caused by network congestion (The reFINE Roadmap, 2013). Solutions for sustainable and durable retrofitting of assets that are based on new low environmental impact materials are part of the strategy. Indeed, application of conventional retrofitting techniques, such as steel or concrete jacketing require intensive labour (high cost) and considerable quantities of materials (higher embodied CO_2 emissions and energy), and significantly disrupt the traffic of the infrastructure asset under renovation. To overcome these issues, advanced materials are required. One of today's SoA techniques is the use of fibre reinforced polymers (FRPs). Despite their well-established advantages (high strength, corrosion resistance, ease and speed of application), the FRP strengthening technique entails a few drawbacks (poor behaviour at high temperatures, high costs, inapplicability on wet surfaces, etc.). To address the problems of FRPs, novel structural materials have been proposed, such as the so-called Textile-Reinforced Mortar (TRM) made of textiles (fabric meshes) impregnated with inorganic binders (e.g. cement-based). Recent studies showed that TRM systems are very promising as a means of strengthening existing concrete structures (Bournas et al. 2009).

4. Implementation of a performance-based approach

The adoption of a performance-based approach as presented above, clearly call for the need of updated data on the health status of the infrastructure considered. This means, in a long-term perspective across the whole life-cycle of the infrastructure, that a huge amount of data will be collected, processed, analysed and stored. However it is clear as well that a huge amount of data on the state of infrastructure assets does not imply by itself to obtain more accurate knowledge and information of the structural health and conditions of the asset. Current data processing tools analyze data separately, generating information in a variety of formats hindering an automated comprehensive analysis. Often, the information about the state of the infrastructure is obtained from design data, either because there is no other information or because there are no suitable tools to analyze available data. Most common data analysis techniques provide information on the state of infrastructure, but do not predict their future evolution.

The need here is for advanced tools that will overcome these limitations through the integration and harmonization of all available data, and by analyzing data from a new point of view: a probabilistic approach. Also, the development of advanced data handling & analysis is needed in order to analyse the impact of failure of sensors in a sensors network (error compensation); compensate cross interference among variables (temperature, cyclic variations, etc.); automate acquisition and supervision process from site to remote server (data stored on cloud) and identify dynamics and damage (at both micro- and macro-scale) together with the definition of thresholds. Moreover, the aim of these tools should be to optimize the use of limited resources available, not only determining the best moment to carry out the necessary interventions, but also setting the frequency of data collection for each specific infrastructure.

The proposed solution for the implementation of these tools focuses on the development of an asset dynamic database combined with advanced processing tools that make it possible to obtain a complete statistical characterization of the asset and to provide the history of the asset (damages, repairs, inspections, etc.). A predictive modelling is required here to provide risk indicators (structural risk, environmental risk, etc.) and probabilistic representation of residual life-time of the component/system. The results of this elaboration will serve as inputs for all the decision-support processes to be developed. This decision mechanism will be used for prioritizing actions/repairs/interventions based on: risk indicators and risk-transfer measures; traffic disruption and social impact; repair costs and available resources for maintenance.

With reference to the proposed risk-based approach, the implementation of an "Operational Risk Assessment" is considered as an essential part for any tool to be used in an Advanced AIM. The analysis on the impact of the risks will be based on (see Figure below): intrinsic risk of the process, measured through the RPN Index (Risk Priority Number) and existing mitigation's elements, measured through the RMI Index (Risk Management Index). Taking the RPN and the RMI into consideration altogether for risks intrinsically critical will enable a global esteem of the actual state of the risk. Afterwards, the outcomes of the Risk evaluation phase will be used to define the proper intervention strategy. The necessary solutions will be defined in detail taking into account the adoption of measures for transfer risks to counterparts. In the risk transfer approach, either the investments to mitigate and reduce the impact of any physical adverse event, and the effectiveness of a substantial and sustainable retention of the risk will be taken into account and identified. This way, quicker and most effective responses to any indication of risk will be taken. With these actions the performance of the transport infrastructure is maximized (at the same time both the risks of the infrastructure and the traffic disruptions are minimized).

Fig. 4. Operational Risk Assessment strategy.

5. Barriers

5.1. Non-Technical barriers: fragmentation & conservative attitude of the construction sector

Although innovations in AIM are strongly needed in the infrastructure construction sector and their implementation, as suggested before, is strongly encouraged, barriers exist that may limit their development. Among the others main non-technical barriers are:

- The market for both infrastructures and the related Research & Development (R&D) activities is still too fragmented in the EU.
- Cooperation between infrastructure providers and managers in Europe is at an early stage.
- Standards for information systems, such as AIM solutions, are largely missing.

Due to this fragmented situation, the role of infrastructure was overlooked in the development of new transport modes. Therefore, better cooperation at European level can yield substantial synergies. The ambition here should be to optimize research efforts on infrastructure networks across Europe (where an infrastructure network already exists) and across transport modes (road/railway). At the same time, government agencies hold a very strong market position, due to strategic importance of infrastructure networks. In this context, there is the need for the introduction of new methods that can be effectively be used to support decisions at high-level thus empowering policy makers to pave the way for their introduction in the sector. This is clearly linked to standards and regulatory regimes that still block the introduction of Advanced AIM solutions and services in the transport and infrastructure sector. Indeed, with ageing European infrastructures, the upgrades of standards and codes to new (more dynamic) regulatory regimes is becoming of paramount importance and cannot be postponed. Research efforts should be devoted to identify gaps in current codes that restrict the introduction of new methods and solutions in the management of infrastructures (The reFINE Roadmap, 2013).

5.2. Technical barriers and how to overcome them

Beside non-technical barriers, there are still technical issues that hinder the impact of advanced AIM solutions. Even in this case, the aim of research efforts should laid into concrete actions to overcome these barriers. Essentially, among the others, the following actions could be considered:

- The objectives of research efforts should be harmonized and identified as specific, realistic and time –bound.
- Technological innovations should follow clear and harmonized objectives not being the result of an industry push but the mitigation of industrial requirements (business continuity) with societal needs (availability of the service)
- Technical risks for their implementation have to be clearly analyzed and assessed together with the identification of actions to mitigate these risks.

6. Impacts & Benefits

6.1. Long-Term Sustainability

Maintenance interventions are mainly focused on structures with a moderate deterioration level, but maintenance investment is focused on moderate to high depth works. With a better maintenance strategy, the amount of necessary maintenance tasks and intervention might be reduced thus contributing to a reduction of lane occupation by worker teams. This will impact on the lanes availability and will contribute in reducing risk of accidents. For example, in Germany, over 8500 roadway bridges have been determined to be re-calculated in the following years considering traffic loads, asset condition and new design codes. In the course of the re-calculation, significant computational deficits are determined (80% of recalculated bridges).

Through the adoption of monitoring measures, service life is expected to be prolonged in 10-15 years' time frame and as a consequence traffic-related compensation measures can be greatly reduced. This is reasonable for infrastructures that are still in good or sufficient conditions (the majority) and that will physiologically degrade or at least will require additional maintenance interventions (and then management costs) in the next years. By Advanced AIM solutions it can be estimated that more than half of these structures (constituting of the majority of the total structures) can be maintained in sufficient conditions and that their lifetime can be prolonged.

This will impact on the long-term value of the asset. Indeed, degradation and ageing effects decrease the asset performances, thus limiting its operability and, as a consequence, its value in time. Maintenance activities need to be performed in order to reinstate the original value of the asset. However, if they are performed according to codes and standards (i.e. on planned intervals as imposed by law's requirements) once they occur the value of the asset could be already at a low level. Therefore significant maintenance activities are required to reinstate the original value (Figure below). On the contrary with the adoption of Advanced AIM grounding on performance-based approaches, the value of the assets, that will in any case physiologically decrease during its lifetime, will be kept as constant as possible. This allows to keep the asset under operation and to ensure the continuity of the business.

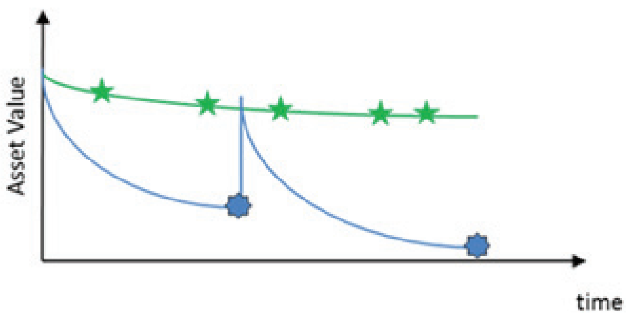

Fig. 5. Long term impact: asset value vs. time: current time-based maintenance approach (blue line); future performance-based maintenance approach (green line).

What this means can be analysed with reference to the data available from the German case study. Indeed in German for maintaining the 39000 total bridges, 470M€ are required per year (Neumann, et al. 2012) which means around 12k€ per bridge. The 70% of these bridges represents the target group for the application of Advanced AIM. Among this 70%, the 75% of these bridges (20400) are those whose lifetime can be prolonged by reducing the maintenance of at least 10%. This means a saving of ~25M€ per year, that can be reallocated for investments in new technologies and materials for keeping the network available longer than estimated.

This brings to the point that this is a social and economic issue. Indeed, unavailability of infrastructures cannot support a healthy economy. Therefore, the implementation of the proposed approach will have a social impact and an economic benefit since it guarantees efficient allocation of investments. Indeed, the approach aims at increasing the availability of such investments (and by consequence the productivity of the network) leading to economic benefits for both the infrastructure manager in terms of business continuity and the users in terms of availability of the service, as visualized in the next figure.

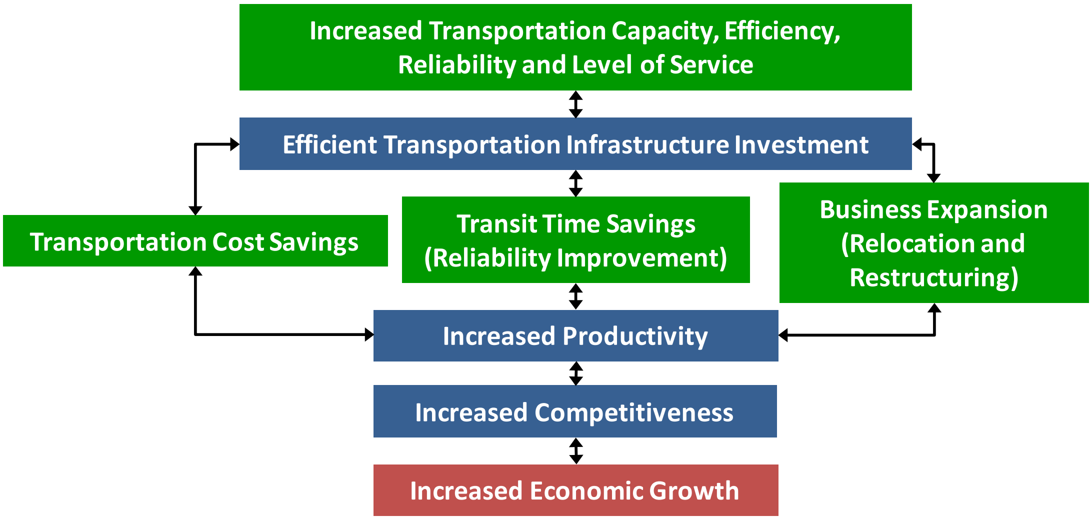

Fig. 6. Potential Social and Economic benefits of implementing the advanced AIM concept.

6.2. Lifetime prolongation and network resilience

As shown above, the adoption of performance based approaches in combination with the availability and use of monitoring data (that can provide updated information on the state of the structure), can be used to trigger inspections autonomously, thus moving from a time-based scheduling of interventions to a performance-based scheduling (interventions/inspections can be performed only when needed). Monitored data can reduce the uncertainty associated with the asset integrity status, thus increasing the reliability of the infrastructure and reducing maintenance costs.

In addition, monitoring information can be used to optimize Life-Cycle Costs (LCC) over the entire lifetime of the infrastructure. Indeed monitoring can minimize the requirements for maintenance providing a better knowledge on structures; it can minimize the requirements for unscheduled maintenance thanks to diagnostic process of the structure monitored; it can predict unscheduled events, thus optimizing the maintenance cycle time and improving upgrades and refurbishments (Frangopol and Liu, 2007).

Finally the adoption of Advanced AIM solutions will impact on infrastructures life cycle on the basis of two principles: Continuous monitoring of the structures and infrastructures performance. Better maintenance strategies by mean of the optimisation of the scope and the timing of the works. A pictorial representation of what does this means is depicted in the following picture in terms of network resilience (continuous line) vs. lifetime prolongation (dashed line).

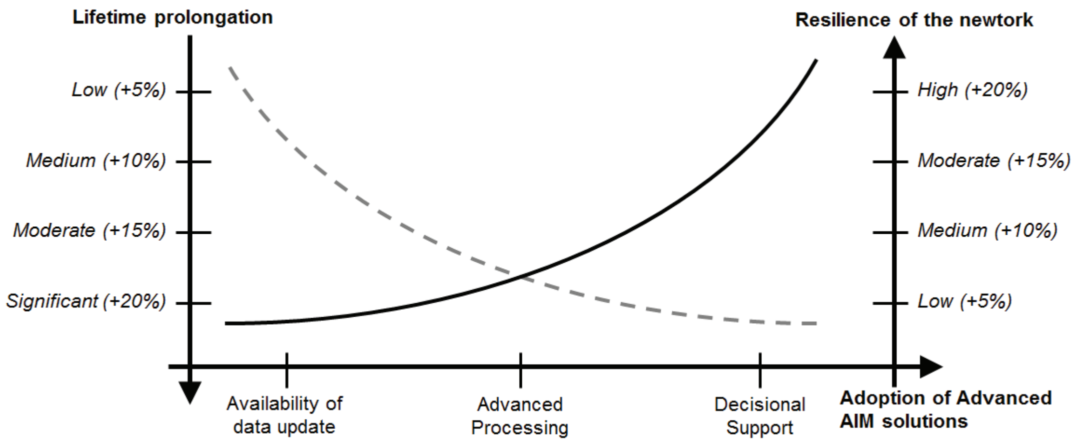

Fig. 7. Impact of Advanced AIM solutions: Network Resilience vs. Lifetime prolongation.

7. Conclusions

Starting from the analysis of the general frameworks and the future trends European Infrastructures are subjected to maintenance tasks, investments, degradation rates, etc.. The present paper proposes a comprehensive Asset Integrity Management (AIM) approach directed at replacing current time-based strategies with a performance-based one in order to systematically take into account the dynamic nature of the transport network, its changes and its needs to be adaptable to current and incoming trends. This with the aim of increasing the life-time of existing infrastructures, prolonging their service availability and reducing costs associated to time-fixed maintenance tasks.

The steps leading to the implementation of such approach are described both from the research perspective and the perspective of infrastructure managers that have to daily deal with the integrity management of their assets ensuring business continuity. Technical and non-technical barriers to achieve it are presented and analysed so that to clearly define the strategy in a long term time frame. This leads to the point that improving the knowledge on existing infrastructure thus reducing uncertainties, is the most effective way to achieve a sustainable impact consisting in optimal balance among available resources and planning of investments in the maintenance and management of European Infrastructures.

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